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Rhythmic Corrugations In Highways

by Vol 45

HOMER J. DANA

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ENGINEERING EXPERIMENT STATION

H V Carpenter, Director

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THE CONTROL OF THE WASHBOARD PROBLEM IN GRAVEL HIGHWAYS

by

Homer J Dana*

Due to the continued increase in motor vehicle transportation, and to the higher average rate of speed at which traffic now moves over the highways, the Maintenance Departments of our Highway Systems are confronted with increasingly serious and difficult problems of maintaining gravel road surfaces One of the most serious of these problems is the rapid formation of successions of ridges or rhythmic corrugations commonly called washboards which are destructive to both roads and vehicles As fast as possible, main traveled roads are being paved, and thus the washboard problem for that particular road is solved, but for every mile of paving being laid down, there remain several miles more of gravel feeders, and these also are being extended The problem, therefore, promises no hope for complete solution by paving, at least for many years

The most effective method of control of the washboard problem, which has been developed to date, has been through intensive maintenance by blading, and by oiling the gravel surface But the cause of washboards still remains, and with increasing traffic the road destruction still continues because the motor vehicles themselves possess the characteristics which are required to make washboards Any type of road is subject to this destructive force, although not all of them give way to it Where breakdown occurs the weakest places give way first.

The Engineering Experiment Station wishes to express appreciation to the Hon. Samuel J. Humes, Director of the Washington State Highway Department, and especially to Mr. Lacey V Murrow, District Engineer at Spokane, for their interest and assistance given toward conducting the tests made during the summer of 1930.

STATE COLLEGE OF WASHINGTON MAKES TESTS

Beginning in 1925 the Engineering Experiment Station of the State College of Washington undertook an active study of the **cause** of washboards with the object in mind to discover if there might not be a **cure** for them by removing or controlling the **cause**. The first report on the work, "Engineering Bulletin No. 19," was published in 1927. This work pointed out the destructive effects of resonance of vibration of car axles and wheels and its relation to speed of travel.

The knowledge gained in the tests thus far appeared to justify the hope that the formation of washboards could be controlled, if not entirely prevented, by control of the functions of the vehicle itself.

This work revealed the rhythmic or resonant character of the forces tending to break down the road surfaces, and indicated the need to study the possibility of controlling or smothering out the tendency of the wheels and axles of the car itself to vibrate vertically Such a study was pursued, resulting in tests with a car on a crushed rock highway to see how long it would take to destroy the road surface under the following conditions·

1. Car equipped with high pressure tires
2 Car equipped with balloon tires.
3 The effect of shock absorbers in No 1 and No 2 above

This resulted in Bulletin No 31, published in January, 1930, in which it was shown that:

1. A car equipped with high pressure tires made "washboards" very rapidly. (50 trips at 40 MPH)

2 "Washboards" were formed much more rapidly at 40 MPH than at 25 MPH (50 and 110 trips respectively.)

3 The use of a certain type of shock absorber on this vehicle very materially delayed the formation of "washboards." (Ratio approximately 2 to 1)

4. The use of balloon tires, either with or without shock absorbers, prevented the formation of "washboards" on the test road even after prolonged travel

These tests, while not yielding conclusive results, gave further encouragement to the belief that the formation of washboards could

be controlled. However, since practically all passenger cars are balloon equipped, and only the trucks use high pressure tires, the next study was devoted to tests with a truck. During the summer of 1930, tests were made on the test highway, using a 1½ ton truck. At the same time a laboratory study was made of the characteristics and behavior of different types of cars, and of the influence of shock absorbers and tire pressure upon their response to rough roads. The results of these two studies are embodied in this, the Third Progress Report, Engineering Bulletin No 36

THE OCCURENCE OF WASHBOARDS

Washboards occur most frequently in dry gravel or crushed rock surfaced highways, although they have also been observed in bitulithic concrete roads and in oil-treated gravel roads as well. Washboards have not been observed to occur in cement concrete road surfaces although the destructive force is always present with traffic on such highways

CAUSE OF WASHBOARDS

The cause of washboards is present at all times and on all types of highway surfaces where there is automobile traffic The cause is inherent in the vehicles themselves.

The body of a car or truck, together with the load, if any, has the greatest weight and inertia of any part of the vehicle Tests show that at customary road speeds, the body of the vehicle, due to its great mass, moves but very little vertically while traveling horizontally over washboarded roads For purposes of the following analysis, the body of the vehicle may be considered to be comparatively stationary vertically because of its large mass One end of the car springs are attached to this practically stationary body and the other ends are attached to the axle and wheel assembly, or what is known as the unsprung weight, which latter is also cushioned by the air pressure in the tires. This combination of large body mass, flexible springs, and the smaller mass of axle and wheels cushioned by air-filled tires, traveling at any customary speed over a highway constitutes a system very responsive to external disturbances and one easily set into periodic vibration

MANY THINGS MAY CONTRIBUTE TO START WASHBOARDS

A small obstruction, or uneveness in the road surface, the lurch of the car, the vibrations of the engine, or any of a number of different circumstances, separately or combined, may cause the wheel and axle to jump from the road surface. It may or may not entirely leave the road surface, but when it descends, the cushioning of the impact by the air pressure in the tire will cause the wheel to bounce again. This bouncing will continue until the original energy imparted to the system has all been absorbed by friction between the leaves of the springs, friction in the tire walls, and shock absorbers if any are used.

TRAFFIC BREAKS DOWN THE SURFACE

The wheels of the next car, hitting the same obstruction, or being influenced by similar circumstances will repeat the previous performance. Thus the impacts of successive tires in nearly the same spots will begin to break and loosen the cemented or compacted gravel surface, and the air currents caused by the moving tires and by the car itself will lift part of the loosened binder and fine material and carry it away, at the same time shaping the remainder into successive waves or corrugations which in turn promote still more and deeper ones The loosened coarser material which remains on the surface acts as an abrasive between the following tires and the still firmly bound road material beneath, thus helping to carry forward the destruction of the road. Ultimately much of the coarser loosened material finds its way to the edge of the road. In this way either the total destruction of the road surface is finally accomplished or frequent blading must be resorted to **with its necessary destructive effect upon the compact macadam road bed.** Because the materials of the untreated crushed rock or gravel-surface highway possess the lowest cohesive strength this type of road as compared to cement or bitulithic concrete, requires the minimum amount of traffic to accomplish its destruction.

RHYTHMIC VIBRATIONS OF CAR MEMBERS CAUSE CORRUGATIONS

The car or truck therefore contains within itself the ever active propensity to destroy the surface over which it travels.

Owing to the fact that when disturbed the "unsprung weight" in a car tends to vibrate more or less periodically, the breakdown of the road surface due to this cause frequently takes on a more or less rhythmic character. Hence the terms "rhythmic corrugations," "ripples," "chatter bumps," or "washboards."

THE INFLUENCE OF TIRE PRESSURES

Tire Pressures and Road Contact Pressures

The contact pressure per square inch of any loaded tire upon the road is equal to the air pressure per square inch within that tire. The contact **area** of a high pressure tire carrying a given load will therefore be considerably less than the contact area for a low pressure tire carrying the same load This contact area is very slightly modified when in motion, by the resistance and inertia of the tire walls themselves, but in average vehicle tires, these are practically negligible and may be ignored.

An increase of the tire pressure on a given car causes the vibratory reactions to appear to be those of a shortened or stiffened spring In other words, the period of vibration is somewhat decreased with an increase of tire pressure On the other hand lowering of the tire pressure gives a reaction the same as if the spring had been lengthened or made more flexible, and therefore the period of vibration is sensibly lengthened For example, on the laboratory machine described hereafter, a Chevrolet front axle, equipped with 3½ inch tires, when vibrating at its natural period was found to vibrate 15 times per second with tire pressure at 64 lbs. per square inch, and 13 times per second with tire pressure at 50 lbs per square inch

HIGH PRESSURE VERSUS LOW PRESSURE TIRES

Table 1

Weight on wheel in pounds	Air pressure in lbs per sq in	Tire contact area in sq in	Work to flex tire 1" over a bump 6 sq in	Upward pressure of bump area on tire	Remaining contact area sq in.	Per cent
750	60	16.5	30 ft. lbs.	360 lbs	6.5	52%
750	35	21.4	17.5 ft. lbs.	210 lbs.	15.4	72%

In Table 1 is shown the comparison between high pressure and low pressure tires on a certain vehicle. It will be assumed that a bump in the road is encountered which makes a contact with a tire of approximately six square inches in area; and that the vehicle is traveling at such a high speed that the wheel is lifted only a negligible amount by the obstruction. Then the upward pressure of the block will be 360 lbs. or 48% of the total load in the case of the high pressure tire, as against 210 lbs or only 28% of the total load in the case of the low pressure tire If the bump were as large as the total contact area, the shock would be the same for both types of tires. (This is slightly modified by the fact that low pressure tires are larger than high pressure tires and therefore contain a larger volume of air, which is reduced in volume a smaller percentage by a given bump)

It is therefore evident from Table 1 that a given small obstruction in the road will cause a smaller disturbing reaction to a low pressure than to a high pressure tire, with consequently greater passenger comfort. At the same time, the vertical travel, or vibration of the wheel and axle will be less and the tire will be less inclined to leave the road surface, with consequent decreased destruction thereof

THE EFFECT OF SHOCK ABSORBERS

Cars Without Shock Absorber Equipment

When the wheel of a car, without shock absorbers or snubbers of any kind, strikes an obstruction in the road it is free to bounce into the air except for its own inertia and the resistance offered by the spring sustaining the body weight As soon as the wheels and axle reach the greatest height the weight and inertia of the body, acting through the springs, forces the wheel to return to the road surface The tendency of the reaction on the body weight, both upon compression and recoil of the springs has been to force the load to a higher position with reference to the road surface However, when the wheel reverses direction of vertical motion and reaches its lowest position in its return to the road surface the load, now more or less unsustained, has commenced to overcome its inertia and has started on its downward movement The constant reaction upon the road surface will consist of two components The first component will be the

weight reaction plus the inertia reaction of the load through the springs and tires upon the road surface. The second component will be the weight reaction plus the inertia reaction due to the downward movement of the unsprung weight The sum of these reactions **at their maximum** will considerably exceed the total weight of the car at rest. In other words, the weight of the car is held up by a series of cushioned blows against the road instead of a steady pressure.

From another standpoint, as long as a wheel maintains uniform contact pressure on the road surface, this contact pressure will equal the weight of the vehicle and load On a rough road which causes this wheel to leave the surface intermittently its total contact pressure upon the road surface during the impact needs to be high enough so that the average pressure over the interval of contact with the road would sustain the weight of the load during the entire time elapsing during one complete vibration In other words, rough roads tend to hasten their own destruction

Referring again to Table 1, it will be noted that 30 ft lbs of work were needed to flex the high pressure tire a given amount as against 17 5 ft lbs for the low pressure tire If the wheel were prevented from rising vertically, all of this work less that represented by friction in the tire walls would be returned as the tire left the bump. However, in actual practice, a certain amount of energy is stored by lifting the wheels and compressing the body springs When one-way type shock absorbers, or snubbers, are used they are effective in absorbing this energy upon recoil only of the springs Two-way type shock absorbers dissipate this energy partly on compression and partly on recoil of the springs The result in either case is that, instead of permitting this stored enery to expend itself in a large succession of vibrations, it is quickly absorbed and the wheel is kept in more nearly continuous contact with the road surface It is readily apparent that if continuously uniform tire contact with the road surface can be maintained, the cause of washboards will be eliminated and maintenance costs will be reduced to an amount only sufficient to restore the road material carried away by dust or thrown to the roadside by air suction of passing tires

Briefly then, low pressure tires greatly reduce the size and violence of the vertical reactions caused by small bumps in the road

surface Furthermor . snubbers and shock absorbers tend to more quickly dissipate the e nergy imparted by road impacts, and therefore help to maintain more nearly uniform and less destructive tire contact with the road surface Both reduced tire pressure and the use of snubbers or shock abso rbers tend to smother successive, or resonant vibrations which, if un hecked, cause long series of rhythmic corrugations to form adjacen to single bumps or depressions in the road surface

TWO PHASES OF PROBLEMS STUDIED IN 1930

The work on washb ard control as carried on during 1930 was divided into two parts During the dry summer months, a 1½ ton Chevrolet truck was ope ted on the same test track used the year before near Spokane, Was ington From these tests data were secured which showed the relation between load, speed, and the time required to corrugate the highway

In addition to the abo tests, a laboratory study was made of the characteristics of many rent makes of cars This information is supplementary to the te s the highway, and will be fully discussed later in this report Di on of the highway tests follows

TRUCK MAKES SHBOARDS ON TEST TRACK

The test track cons of a section of highway 1 4 miles long, practically level and nearl ght throughout its length See Figure 1.

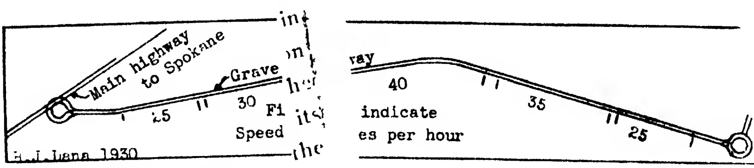


Figure 1 The test highway wa o and four tenths miles long and was divided into five different sections on of which a certain speed was always maintained during the tests Not e intervals between sections reserved for accelerating and decelerating

The road was surfaced sev l years ago with fine gravel screened from a glacial deposit The b. is hard and well cemented and was planed smooth with a grader . Figure 2

The two inches of fine m rial left by the grader was spread evenly over the surface by mean a drag, Figure 3 A final treatment

was given the surface by means of a weighted smoothing drag, Figure 4, which left the track smooth and entirely free from drag ripples

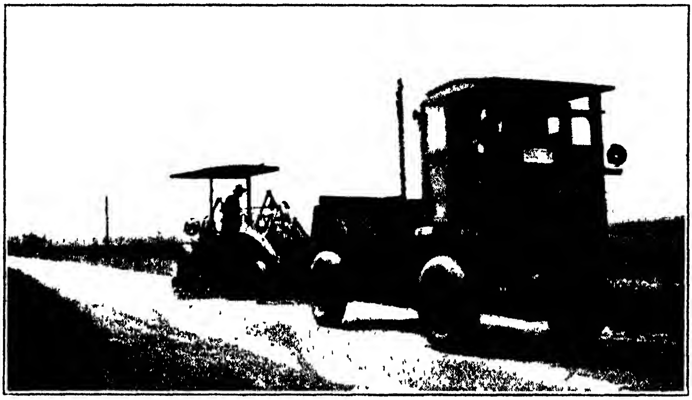


Figure 2 Showing the method of producing a smooth hard base on the test road prior to making the tests

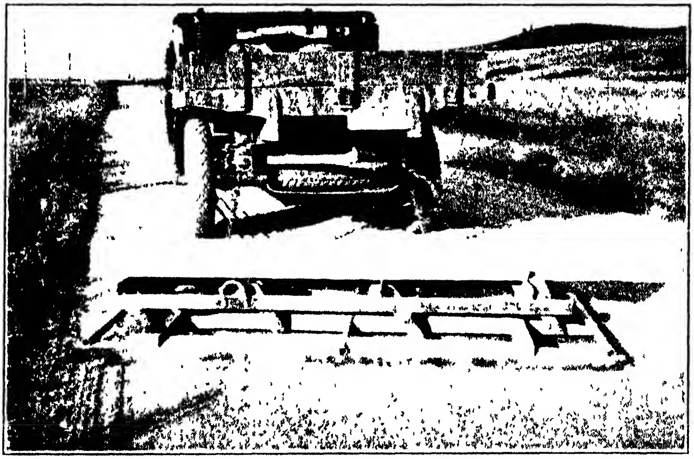


Figure 3 The weighted drag used to spread the loose material evenly over the test road, prior to starting a new test

The test was then started by driving the $1\frac{1}{2}$ ton truck, Figure 5, back and forth over the test road at the speeds indicated in each of the different sections, Figure 1 The driver was trained to watch for the

first indication of washboards, and to make a note thereof in the log, and to record the speedometer reading and the place of occurence. From time to time further changes on the road surface were noted, together with the speedometer reading, so that each event could be identified in terms of trips over the road. The traffic in both directions was concentrated on one track.

Figure 4 A weighted smooth drag was used to give a final smoothing treatment to the loose gravel surface before a test was started

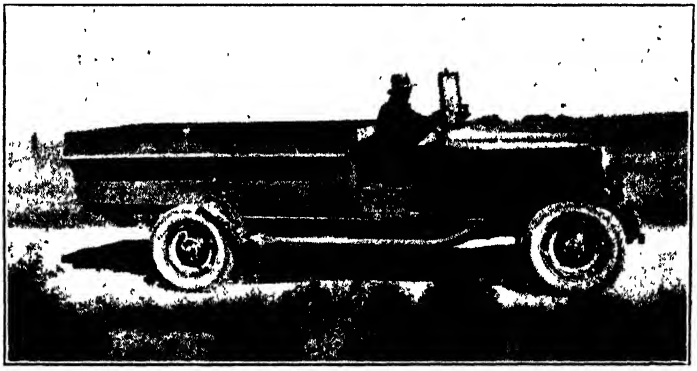


Figure 5. The one and one-half ton truck used in the 1930 tests. The special body plus a load of loose rock totaled approximately 1500 lbs.

1930 TEST DATA

In Table 2 are shown the data in chronological order as secured from the nine different tests made with the truck.[1] In Table 3 are shown the averages derived from the data in Table 2.

Table 2. Truck Test Data

Test No.	Loading	Shock Absorbers	Tire Pressures	Trips to Make Washboards 40 MPH	35 MPH	30 MPH	25 MPH	Total Test Trips
1	1500lb	None	80	40	83	100	163	246
2	None	None	80	30	121	121	151	258
3	None	None	80	29	108	190		203
4	None	None	80	48	63	63	203	211
5	1500lb	None	80	42	139	94	178	184
6	None	One-way	80	138	250	205	270	387
7	1500lb	One-way	80	54	94	336	470	560
8	1500lb	Two-way	80	66	173	215	644	896
9	1500lb	Two-way	65	No change in road surface				660

Table 3. Average Results of Tests

Loading	Shock Absorbers	Tire Pressures	Av Trips to Make Washboards 40 MPH	35 MPH	30 MPH	25 MPH	Number of Tests	Total Test Trips
None	None	80	36	131	125	177	3	672
1500lb	None	80	41	111	97	170	2	430
None	One-way	80	138	250	205	270	1	387
1500lb	One-way	80	54	94	336	470	1	560
1500lb	Two-way	80	66	173	215	644	1	896
1500lb	Two-way	65	No change in road surface for better or for worse				1	660

DISCUSSION OF TEST DATA

An inspection of Table 3 will reveal that the addition of 1500 lbs. load on the 3200 lb. truck seemed to make no marked difference in its destruction of the road surface. This may be due to the fact that the percentage increase in total weight due to the addition of the 1500 lb. load was of less significance than the relatively high tire pressure as regards destructive effect upon the road surface It will be under-

[1] Weight of truck without load—3200 lbs.

stood that reliable and conclusive relative averages should be based upon a very large number of tests, but time and equipment did not permit of more tests being made.

The two types of shock absorbers used appeared not to exert any high percentage of influence in the control of washboards at the higher speeds. However, there is a marked delay apparent at low speeds of 25 and 30 MPH. Time did not permit making tests with other types of shock absorbers or at different adjustments of the shock absorbers used. It is quite possible that the shock absorbers used may not have been operated at their optimum adjustment for this particular vehicle

However, the most significant thing to be noted from Table 3 lies in the last item listed At the conclusion of the previous test, when the road had been badly washboarded in spots, and the track was well worn throughout its length, the tire pressure was reduced to 65 lbs Other conditions remained the same, and without rebuilding the road the test was continued While definite progress from hour to hour could be noted in the destruction of the road surface during the previous test, with reduced tire pressure, **all further destruction appeared to have been halted.** Continued traffic neither improved the condition of the track nor made it worse—in other words, **the destructive forces appeared to be under complete control.** This agrees with the evidence obtained in previous tests with passenger cars on the same test highway, which showed that in no case was it possible to produce washboards with balloon tires See Bulletins No 19 and No 31

LABORATORY STUDY OF AUTOMOBILE CHARACTERISTICS

In order to understand how best to control the washboard-making tendencies of automobiles it is necessary to be familiar with the performance of their various parts while in the act of making washboards A limited study can be made of a car on the highway—but this has the disadvantage that no one set of conditions can be maintained on the highway for a suitable length of time.

LABORATORY MACHINE NEEDED FOR STUDY

For this purpose a laboratory machine was needed, with which a car could be operated continuously under a given set of conditions For instance, the car should be operated as if it were traveling at some given speed over some uniformly spaced washboards of a certain uniform depth. Under these conditions, a study could be made of the effect of varying tire pressure, and the influence of load, and the control of shock absorbers, etc. Such a machine was constructed and studies made of a large number of cars of different makes and sizes. Figure 6 illustrates the principle of this machine and the manner in which it operates to vibrate one end of a car at a time as if it were traveling over perfectly spaced washboards of a uniform depth

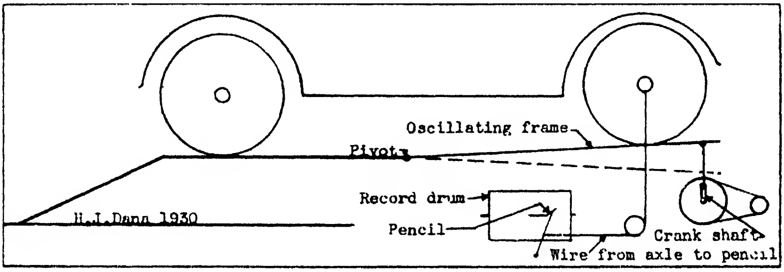


Figure 6 A line drawing of the laboratory machine termed a "jigger," for studying characteristics of cars when traveling over rough roads Note that the "depth" of the washboard is governed by the distance of the wheel from the pivot of the machine frame

CONVERTING MACHINE REVOLUTIONS TO EQUIVALENT WASHBOARDS

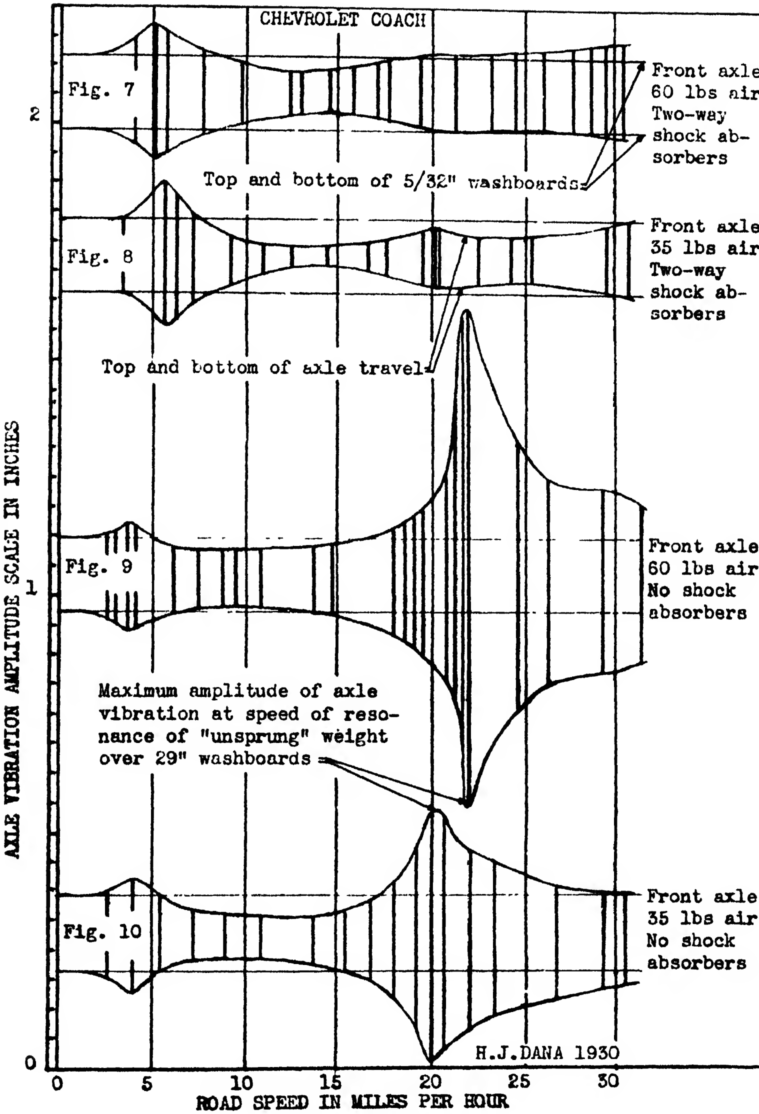
The average length of washboards from crest to crest, as represented by the average of a large number of measurements made on different highways throughout the states of Washington and Idaho, is twenty-nine inches. A car traveling, for instance, at 30 MPH, will pass over 1092 average length washboards each minute. Therefore, in Figure 6, if the crank shaft is rotating at 1092 RPM, the car will be vibrated at the same speed as if it were traveling at 30 MPH over an average washboard highway. On the machine, however, the effect of the lurch of the car, of engine vibration, etc , are eliminated and a study can be made of any chosen set of conditions

METHOD OF MAKING RECORDS ON LABORATORY MACHINE

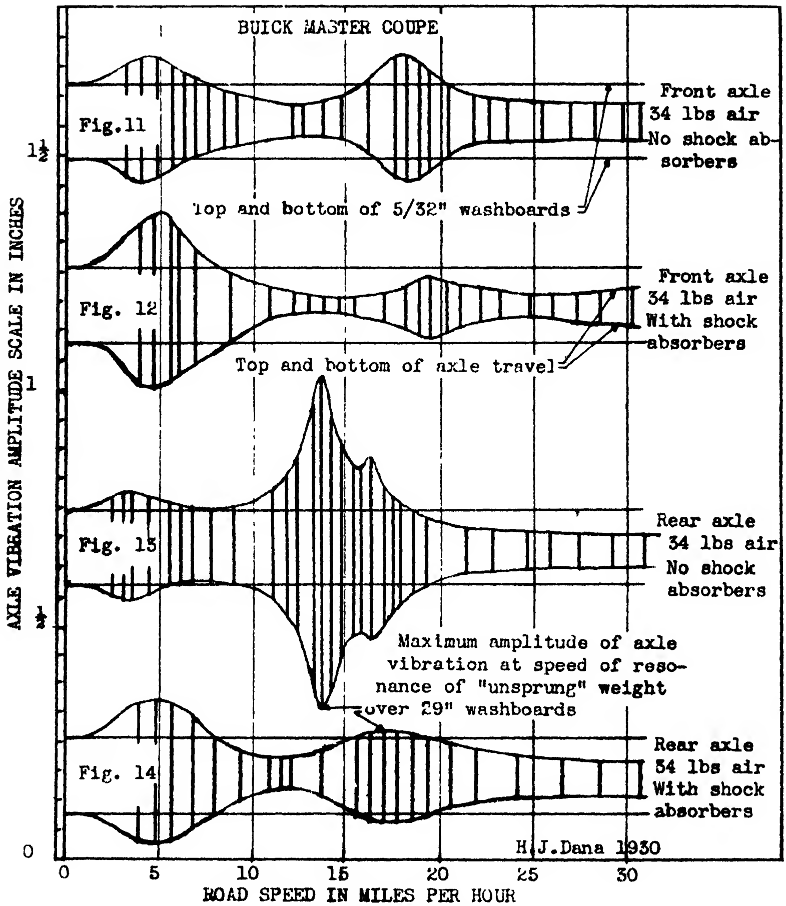
In the following pages are given representative illustrations of records taken from different cars. A record paper with uniformly parrallel lines which are used to represent intervals on the speed axis of the record, is mounted on the record drum. Then the motor is started, and while the machine is vibrating at some speed, say the equivalent of ten miles per hour, the record drum is turned by hand until the ten mile line on the record is under the pencil The latter is then pressed lightly against the record and will mark a line of some certain length The speed is then increased to a slightly higher value, and another line made at the corresponding speed on the chart When the entire speed range has been covered, the chart will consist of a series of different length lines To complete the chart, an envelope is then drawn by hand through the ends of all the lines as shown in Figures 7 to 20, inclusive To show the relative amplitude, or depth of the washboards, the crank shaft is rotated by hand to place the hinged frame member at its highest position. With a car on the machine, and a wire attached to the axle and connecting to the recording pencil, the latter will take a position indicating the extreme top of the washboards In this position the record drum is rotated and a line drawn on the record The same is done with the crank shaft rotated to its lowest position

SIGNIFICANCE OF RECORDS

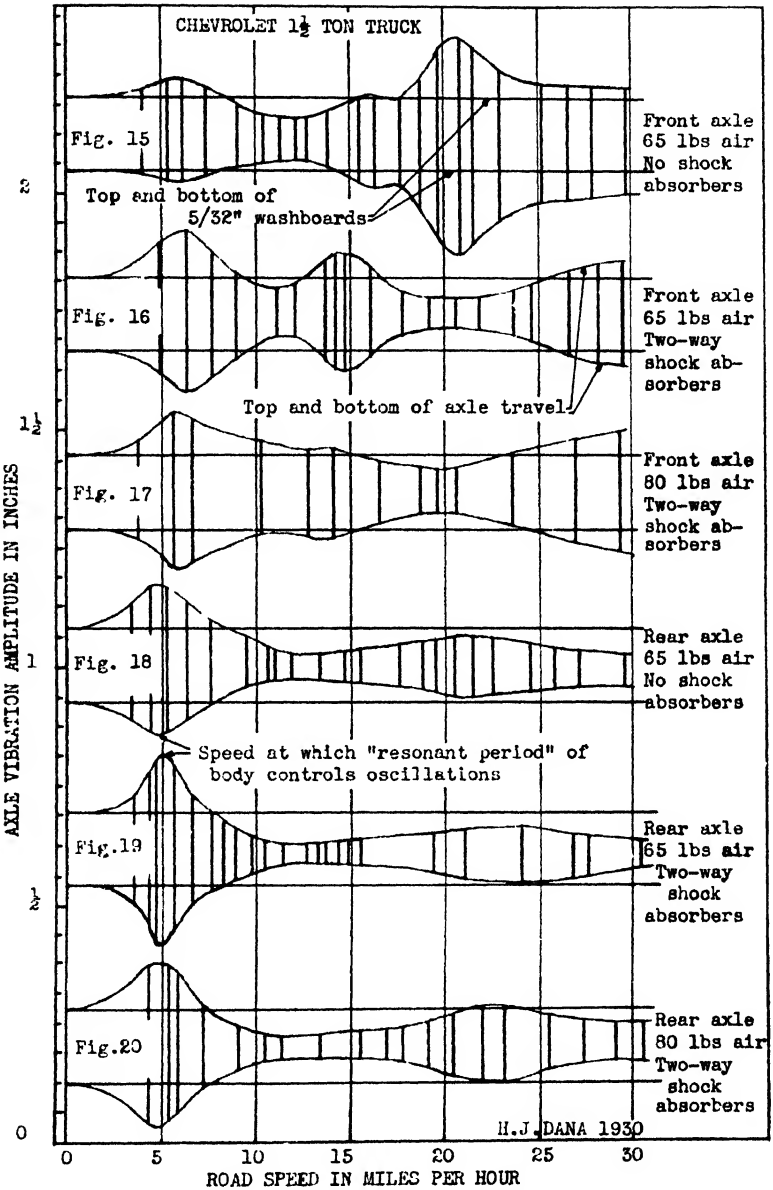
Refer to Figure 9 and note the performance of the front axle of the car in question, a Chevrolet coach having no shock absorbers, and with tires pumped up to 60 lbs per square inch, when traveling over perfectly spaced washboards only 5/32" deep At about 4 MPH, the resonant period of the body is controlling the situation At 10 MPH the axle movement has become reduced to a distance less than the depth of the washboards being traveled over However, at 22 MPH, the resonant period of the unsprung weight is reached, and the axle vibrates with an amplitude several times greater than the depth of the washboard. At 30 MPH, the amplitude has been materially reduced, although it still is greater than the depth of the washboard. The limitations of the machine used for this work prevented operation at



Figures 7 to 10 inclusive



Figures 11 to 14 inclusive



Figures 15 to 20 inclusive

higher speeds than those shown. Improvements are contemplated, however, which will permit studies at much higher speeds.

As a contrast, note the measure of control evidenced in Figure 7. Without a doubt, at resonant speed, the destructive effect of this condition upon the road surface is much less than in the case of Figure 9 Incidentally, passenger comfort probably would be much greater also. The effect of lowered tire pressures will be noted in Figures 8 and 10.

In Figures 11 to 14 inclusive, is shown the measure of control afforded by a one-way shock absorber of the snubber type No particular significance should be attached to the shape of the curves at 4 to 5 MPH since that is a speed below normal operation. The charts were completed to the zero point because that offered a definite terminus. In Figures 11 and 13 the axles of the Buick coupe under test are uncontrolled and, at the speeds of 25 MPH and higher, over washboards 5/32" deep oscillate with an amplitude no greater than when controlled by one-way shock absorbers of the snubber type. See Figures 12 and 14 Therefore, at the normal driving speeds of 25 MPH and higher over washboards 5/32" deep scarcely any apparent benefit accrues from the use of shock absorbers on this balloon tire equipped car. However, at the speed of resonance for either axle the shock absorbers exercise a decidedly restraining influence. At the higher speeds over deeper washboards, tests show that shock absorbers do exercise a certain measure of control over axle vibrations

Figures 15 to 20, inclusive, show the characteristics of a Chevrolet 1½ ton truck carrying a load of 1500 lbs The normal air pressure in the tires for full load was 80 lbs In Figures 17 and 20 the two axles were vibrating under the restraint of two-way shock absorbers having equal reactions both for compression and recoil. At a highway speed of 30 MPH it is apparent that the front axle was more active than the rear and at the reduced air pressure of 65 lbs , the same condition obtains as shown in Figures 15 and 18. Shock absorbers on the rear axle of this car make comparatively little change in amplitude of vibration, while for the front axle a marked change in performance is noted at certain speeds. At the road speed of 30 MPH however, but very little restraint resulted from shock absorbers when traveling over 5/32" washboards.

In Figure 21 is shown a study of the behavior of a light car using high pressure tires. The curves were determined from the maximum amplitude of vibration at the resonant period of each axle at each tire pressure indicated. The use of hydraulic shock absorbers on this car shows a large percentage of control, with the rear axle the more active in road destruction. If amplitude of vertical vibration can be effectively smothered, then washboards will be prevented from forming

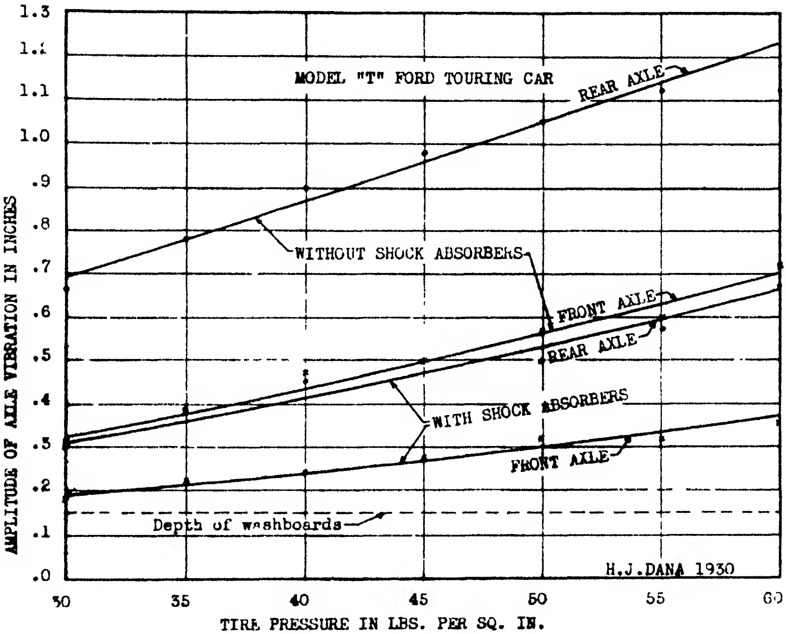


Figure 21 Model T Ford touring car equipped with 30 x 3½ high pressure tires. This type car was usually driven without shock absorber equipment. Note the relation between the depth of the washboards, namely, 156″, and the amplitude of vibration of the uncontrolled axles. On deeper washboards these tires would undoubtedly leave the road surface frequently. These curves were made at the 'resonant' speed of each axle at the tire pressure indicated.

In Figure 22, it is evident that the front axle is more active than the rear but the difference between the two is not so great as in the case of Figure 21. The "natural period" of vibration of the front and the rear axles of this car at 34 lbs. air pressure and with shock absorbers occurs at 19.5 and 16.7 MPH respectively.

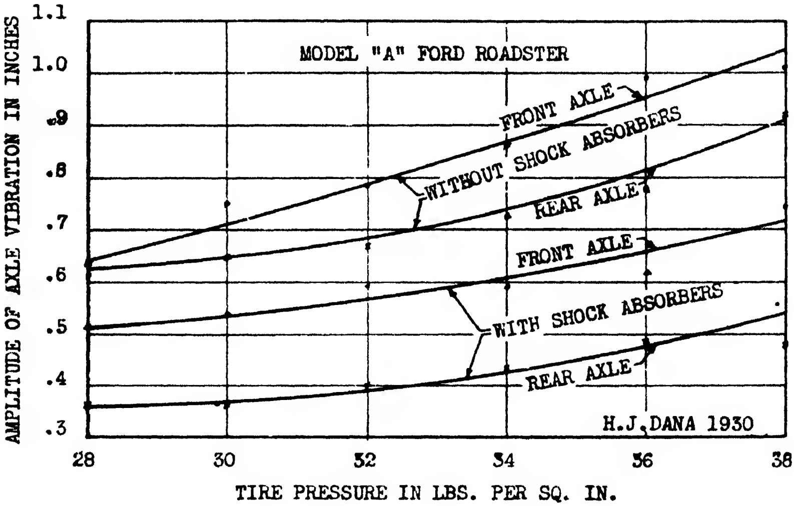


Figure 22. The amplitude of axle vibration in inches was taken at the resonant speed, which corresponds to approximately 20 MPH for the front axle and 17 MPH for the rear axle when traveling over 29" washboards, 156" deep The tires are balloons, size 30 x 4 50

In a heavier car, the inertia of the body can be utilized to a greater degree to control axle vibration. Figure 23 shows the control realized from the use of shock absorbers, the percentage being much larger than in the case of either of the preceding lighter cars It will be noted that the percentage control on the front axle is also considerably greater than on the rear axle

In Figure 24 is shown the comparative control afforded by a hydraulic shock absorber at the different settings from "closed" to virtually "wide open."

It is recognized that the consideration given in the past by the public to shock absorbers of any kind was on the basis of improving the riding and driving qualities of the vehicle itself. Fortunately, it appears that the use of shock absorbers has a more or less beneficial effect toward the suppression of the washboard-making tendencies of the car and that the greater the damping action of the shock absorber, the more effective is it in suppressing washboards.

Briefly then, tests have indicated that to prevent washboards, it is necessary to restrain the vertical vibration of the axle to a minimum. This means that the tire itself must be compelled to absorb the major part of the road surface roughness. This, in turn, would suggest the question as to the importance of tire size as related to load and tire pressure The larger the tire section the lower may be the tire pressure and the greater will be its shock absorbing capacity for a given load. Extreme tire sizes, on this basis, of course are not economically advisable, or mechanically desirable.

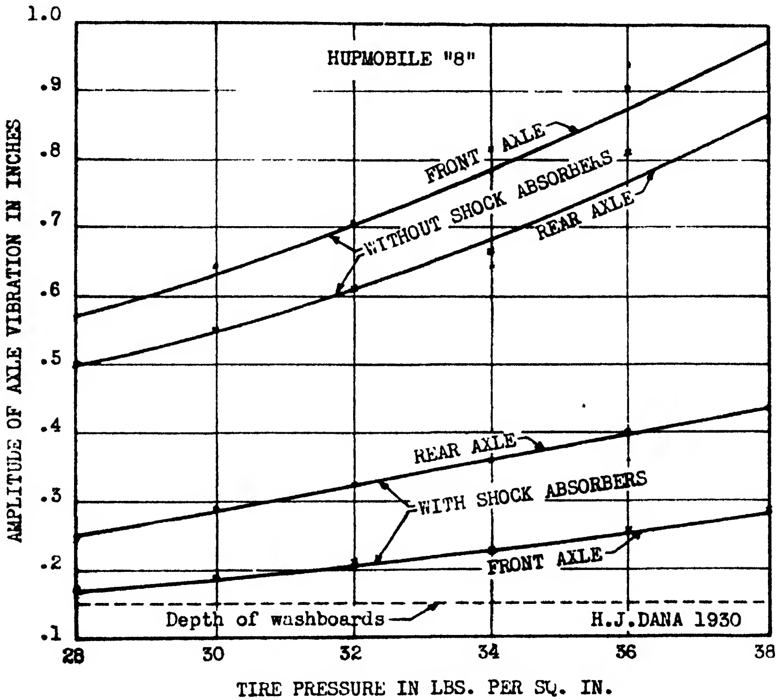


Figure 23. This shows the control exercised by a hydraulic type shock absorber over the vibration of the axles of a sedan car when traveling at resonant speed over 29" washboards .156" deep. Tires—19 x 6 00; normal tire pressure 36 lbs. This car has two-way hydraulic shock absorbers as standard equipment. Note depth of washboards as indicated by broken line at amplitude of .156.

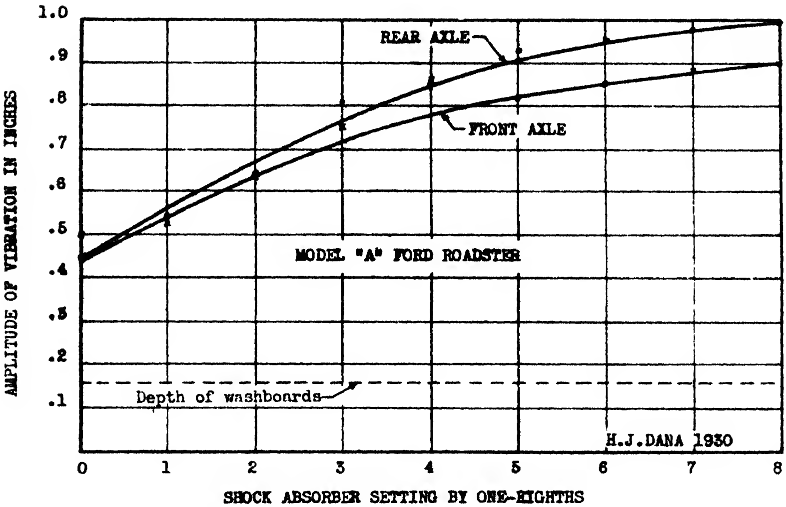


Figure 24 The extent to which a hydraulic type shock absorber can control the axle vibration of a car when driven at "resonant" speed over 29" washboards 156" deep

CONCLUSIONS

The tests thus far have yielded the following information:

1. Trucks and passenger cars, equipped with high presure tires will readily make washboards in gravel or crushed rock highways.

2. Increasing the speed of travel greatly accelerates the formation of washboards.

3 Shock absorbers, in so far as tests have shown, do afford a certain limited degree of beneficial control over high pressure tires to delay the formation of washboards, but they do not prevent their ultimate appearance

4. Balloon tires, on a light passenger car, were shown by tests to be effective in preventing the formation of washboards on an initially smooth gravel road

5. Reduced tire presure, together with two-way shock absorber control on a truck, definitely halted the destruction of a road which was being badly washboarded by the same truck with high pressure tires.

VALUE AND NECESSITY OF ADDITIONAL STUDIES

Inasmuch as the normal speed of traffic over gravel and crushed rock highways is at 40 MPH and better, the limitations of the laboratory machine, or "jigger," has prevented the studies being extended to cover the present day customary rate of travel. These studies will be extended at the earliest possible date.

Study of the washboard problem has shown conclusively that certain characteristics of pneumatic tired vehicles are responsible for making washboards; that speed and high pressure tires are favorable toward increasing that ability; that shock absorbers oppose this propensity; and that low pressure tires do prevent the formation of washboards

However, some of the questions still unanswered, are:

1 What is the highest tire pressure permissible, and still keep the vehicle from making washboards?

2 What, if any, is the relationship between tire size and its washboard making tendency?

3 Is there some type of shock absorber which would be more effective in the prevention of washboards?

4 Is there a maximum load limit beyond which it is impossible to prevent the formation of washboards

5 What is the relative destructiveness of trucks and stages as compared to private passenger cars?

6 To what extent can the washboard-making tendencies of a car or truck be controlled at the higher speeds now common on the highways—say up to 60MPH?

STATE COLLEGE OF WASHINGTON TO CONTINUE TESTS

As rapidly as time and finances will permit, the Engineering Experiment Station of the State College of Washington proposes to carry the study of the Washboard Problem to a definite conclusion.

Engineering Bulletins
Published by the Engineering Experiment Station
State College of Washington

1. Sewage Disposal for the Country Home. (Out of Print.)
By O. L. Waller and M. K. Snyder, March, 1914, July, 1916.

2 How to Measure Water.
By O. L. Waller, October, 1915, Reprint 1925 (Revised and Reprinted as part of Engineering Bulletin No. 20.)

3. Water Supply for the Country Home. (Out of Print.)
By M. K. Snyder See Engineering Bul. No's. 9, 10, and 11.

4. Construction and Maintenance of Earth Roads.
By L. V. Edwards, April, 1916.

5 Cost of Pumping Water. Reprinted as Extension Bulletin No. 103
By O. L. Waller, August, 1916.

6 Fuel Economy in Domestic Heating and Cooking.
By B. L. Steele, December, 1917.

7. Thawing Frozen Water Pipes Electrically.
By H. J. Dana, October, 1921.

8 Use of Ropes and Tackle, Illustrated
By H J. Dana and W. A. Pearl, December, 1921

8 Well and Spring Protection.
By M. K. Snyder, July, 1922.

10. Water Purification for the Country Home.
By M. K. Snyder, February, 1922.

11. Farm Water Systems.
By M. K Snyder and H J. Dana, January, 1923.

12 Commercial and Economic Efficieny of Commercial Pipe Coverings. By H. J. Dana, 1923.

13 Critical Velocity of Steam With Counter-Flowing Condensate.
By W. A Pearl and Eri. B. Parker, February, 1923.

14. The Use of Power Fans for Night Cooling of Common Storage Houses. H J. Dana, December, 1923.

15 A New Stationary Type Laboratory Meter.
By H. V. Carpenter and H. J. Dana, September, 1924.

16. Relation of Road Surface to Automobile Tire Wear. First Progress Report By H. V. Carpenter and H. J. Dana, January, 1924.

17. Relation of Road Surface to Automobile Tire Wear. Second Progress Report By H. J. Dana, December, 1925.

18. Relation of Road Surface to Automobile Tire Wear. Third Progress Report. By H. J. Dana, October, 1926.

19. Rhythmic Corrugations in Highways. First Progress Report.
By H. V. Carpenter and H. J. Dana, February, 1927.

20 How to Measure and Use Water for Irrigation.
By O. L. Waller, March, 1927.

21. Magnetic Nail Picker for Highways.
By H. J. Dana, August, 1927.

22. Spray Residue and Its Removal From Apples. By F. D. Heald, J. R. Neller and F. L. Overley of the Agricultural Experiment Station in Cooperation with H. J. Dana.

23. Survey of Fruit Packing Plants. ($2.00 each) By H. J. Dana, December, 1927

24. Survey of Fruit Cold Storage Plants. (Out of Print.) By H. J. Dana, March, 1928

25. An Extensometer and Compressometer of the Hydro-static Type By H. H. Langdon, October, 1928

26. A Survey of Fruit and Cold Storage Plants in Central Washington By H. J. Dana, December, 1928

27. The Automatic Underfeed Coal Stoker for Domestic Heating. By Homer J. Dana, April, 1929. Second Edition, October, 1929

28. Importance of Preliminary Ore Analysis by Means of the Stereoscopic Binocular Microscope. By Arthur E. Drucker, April, 1929

29. Short Wave Transmitter Design By David H. Sloan, September, 1929. 25c postpaid

30. The Elasticity of Concrete By Howard H. Langdon, January, 1930

31. Rhythmic Corrugations in Highways. Second Progress Report By Homer J. Dana, January 1930

32. The Economical Distribution of Steam in District Heating By A. C. Abell, February, 1930

33. Application of Stellite to Agricultural Tools. First Progress Report. By G. E. Thornton and C. C. Johnson, September, 1929

34. A Study of Welded Metals Under Fatigue Tests. By G. E. Thornton, April, 1930

35. Electro-Hydrometallurgical Process For Copper Flotation Concentrate. By Arthur E. Drucker and Carl F. Floe, April 1930

36. Rhythmic Corrugations in Highways. Third Progress Report By Homer J. Dana, December, 1930

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A Method of Compiling Approximate Mining Cost Data

by

Guy E. Ingersoll

School of Mines and Geology

ENGINEERING BULLETIN NO. 37

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

October, 1931

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "**to further the application of the principles of physical science to industrial pursuits.**" The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911 This was followed by later appropriations In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service The last named includes tests and analyses of coal, tests and analyses of road materials, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc

Bulletins are available as listed on pages 22 and 23

Requests for copies of the engineering bulletins and inquiries for information on engineering and industrial problems should be addressed to The Engineering Experiment Station, State College of Washington, Pullman, Washington

The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

A METHOD OF COMPILING APPROXIMATE MINING COST DATA

by

Guy E. Ingersoll

In order to best serve their purpose, mining costs should be available soon after the work which they cover has been done, and at frequent intervals. If at any time the costs of a particular operation are high, this should be known at once in order to determine the reason, and to correct it, if possible, before a large loss occurs. In many ore bodies the metal content varies gradually and there is no sharp distinction between ore and waste. For a given mining cost a certain grade of material can be mined at a profit and will be considered ore. If the cost of mining this can be decreased a lower grade of material can be mined as ore. If the official in charge of a mining property is kept advised at frequent intervals of the costs in the various working places, the distinction between ore and waste can be accurately maintained. The property as a whole may be operating at a profit but if a certain ore body is being mined at a loss this should be known and corrected at once. The difference between success and failure of a mining property may depend upon a close watch of the costs of the various operations.

The cost of operation of a mining property is made up of three elements: labor, supplies, and "expenses." The labor costs may be obtained from the payroll, the cost of supplies from the various operations may be obtained from the warehouse records; and "expenses" may include such items as power, shops, laboratory, liability insurance, and tool sharpening.

If these data were collected at frequent intervals such as four times a month, the figures for the first three periods would probably be approximate and adjustment could be made when the fourth period costs were obtained with the figures for the entire month. The cost to the accounting department of compiling the cost sheets four times

a month, instead of once a month, is to be considered. Experience has shown, however, that the advantages gained by this extra work more than pays for the extra clerical work

In order to have a basis for comparison of the costs from period to period, the average cost, for each operation, over the previous six months' period may be shown under the heading of "Average Period"

The data for this paper were furnished by an official of a large mining company The writer is not at liberty to disclose the identity of the official or the company, but wishes to express here his appreciation for the courtesy The writer also wishes to acknowledge his thanks for the helpful suggestions of Professor C R Ham, of the Department of Business Administration of Washington State College

This method of approximate cost accounting can best be explained by illustrating its use at an imaginary mining property, which we shall call "The Hypothetical Mine," operated by the Hypothetical Mining Company. A concentrating plant is operated on the property and the concentrates are transported by an aerial tramway to the nearest railroad shipping point

Table 1. Hypothetical Mining Company. Approximate Cost Data.

Mine Operating—Breaking Ground "A" Ore Body

Period: Feb 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor	4819 04	3003.81	3003 81	.9856	.4092	.4092
Supplies	2425.76	1889 39	1889.39	.4961	.2574	.2574
Expenses	1789 52	2662 47	2662.47	.3660	.3628	.3628
Total	9034.32	7555.67	7555.67	1.8477	1.0294	1.0294
Developmt	2164.64	2327 98	2327.98	.4427	.3171	.3171
Total Cost	11198.96	9883 65	9883.65	2.2904	1.3465	1.3465
Tons Ore Broken	4890.00	7340.00	7340.00			

The operations at this porperty may be classified under the following headings: "Breaking ground," Producing ore," "Milling ore," and "Tramming concentrates."

There are three ore bodies being mined at this property which we shall designate as "A" ore body, "B" ore body," and "C" ore body. Costs are kept separately on these three ore bodies

Table 2. Hypothetical Mining Company. Approximate Cost Data.

Mine Operating—Breaking Ground "B" Ore Body

Period: Feb. 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor		922.71	922.71		.4773	.4773
Supplies		428.81	428 81		.2218	.2218
Expenses		679 05	679.05		.3513	.3513
Total		2030.57	2030.57		1.0504	1.0504
Developm't		3007.61	3007.61		1 5560	1 5560
Total Cost		5038 18	5038.18		2.6064	2.6064
Tons Ore Broken		1933 00	1933 00			

Table 3. Hypothetical Mining Company. Approximate Cost Data.

Mine Operating—Breaking Ground. "C" Ore Body

Period: Feb 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor		819.85	819 85		.2523	.2523
Supplies		501.46	501.46		.1543	.1543
Expenses		559.17	559.17		.1720	.1720
Total		1880 48	1880.48		.5786	,5786
Developmt		1007.53	1007.53		.3100	.3100
Total Cost		2888.01	2888.01		.8886	.8886
Tons Ore Broken		3250.00	3250.00			

Tables 1, 2, and 3 show the costs of Labor, Supplies, and Expenses "Labor" includes the wages of all men actually working in the stopes of this ore body as well as the proportion of wages or salaries chargeable to the operation, such as superintendent, foreman, engineers, blacksmiths, mine clerks, etc.

"Supplies" includes the cost of all supplies issued for use in the operation, together with the proper proportion of the costs of other supplies used, which should be charged to it.

"Expenses" includes the costs of electric power, compressor plant, shops, laboratory, trucking, liability insurance, drills and equipment, and tool sharpening.

Under the headings "Total Money" and "Cost per ton of crude ore" figures are shown for "Average Period" This gives the average cost for a period during the previous six months "Cumulative for Month" is the total amount for the month of any item which in Table 1 is the same as for the period inasmuch as it is the first period in the month, but in Table 4 it will be the sum of the costs for that period and the previous periods of the month Thus in Table 1 the labor cost for the period was $3003 81 and the average labor cost per period during the previous six months was $4819 04 The tonnage of ore

Table 4. Hypothetical Mining Company. Approximate Cost Data.

Mine Operating—Producing Ore "A" Ore Body

Period: Feb 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor	3131.87	3836 48	3836.48	.5357	.4374	.4374
Supplies	308.85	244.49	244.49	0526	0279	.0279
Expenses	598.00	873.24	873.24	.1023	.0995	.0995
Total	4038.72	4954.21	4954.21	.6908	.5648	.5648
Tons Ore Produced	5846.00	8772.00	8772.00			
Net Tons to Mill	5846.00	8772.00	8772.00			

broken for the period was 7,340 and for the average period it was 4,890 tons This gives a labor cost of $0.4092 per ton for the period and for the average period the labor cost per ton was $0 9856

The "Cost per Ton of Crude Ore" is obtained by dividing the total money for any item or items by the number of tons broken for the period.

Table 5. Hypothetical Mining Company. Approximate Cost Data.
Mine Operating—Producing Ore "B" Ore Body

Period: Feb 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor		816 70	816 70		3461	3461
Supplies					.0000	.0000
Expenses		177 21	177.21		.0751	0751
Total		993 91	993.91		.4212	.4212
Tons Ore Produced		2360.00	2360.00			
Net Tons to Mill		2360.00	2360.00			

Table 6. Hypothetical Mining Company. Approximate Cost Data.
Mine Operating—Producing Ore "C" Ore Body

Period: Feb 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor		738 90	738 90		.9584	.9584
Supplies		-	--		.0000	.0000
Expenses		243.35	243.35		.3156	.3156
Total		982.25	982.25		1 2740	1.2740
Tons Ore Produced		771.00	771.00			
Net Tons to Mill		771.00	771.00			

Tables 4, 5, and 6 show the costs of "Producing Ore" in ore bodies "A," "B," and "C" respectively for the period February 1 to 8, 1930. These costs are assembled on the same basis as those in Tables 1, 2, and 3. "Producing Ore" as used here refers to the operation of drawing the ore from the chutes of the stopes, hauling it to the shaft, hoisting it to the surface and delivering it into the mill bins. The tonnage of ore as broken and produced is in wet tons and we may assume that the ore contains 2% moisture.

Table 7. Hypothetical Mining Company. Approximate Cost Data.

Mill Operating

Period: Feb. 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor	1187.50	1617.96	1617.96	.2094	.1261	.1261
Supplies	2175.34	1813.92	1813.92	.3803	.1413	1413
Expenses	1753.77	2259.02	2259.02	.3066	.1761	.1761
Total	5116 61	5690.90	5690.90	.8963	.4435	.4435
				% Cu.	% Cu.	% Cu.
Tons Ore Milled	5270.00	12831.00	12831.00	1.9664	1.3381	1.3381
Tons Concentrates Produced	130 00	672.8600	672.8600	24.3197	23.0600	23.0600
Tailings % Cu				.1574	.1360	.1360

Table 7 shows the cost of concentrating the ore at the mill for the period February 1 to 8, 1930, based upon "Labor," "Supplies" and "Expenses" The tons milled, is given in dry tons, which is in this case 12,831 tons. The ore as delivered to the mill bins, as before mentioned, contains 2% moisture As in the other tables the average period is calculated for the operations of the preceding six months and gives a basis for comparison of the costs for the period.

Table 8 shows the cost of transporting the concentrates via aerial tram from the mill to the railroad station. The fifth line of this table

Table 8. Hypothetical Mining Company. Approximate Cost Data.

Tramway Operating

Period: Feb. 1 to 8, 1930 **Date:** Feb 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor	490 96	720.26	720.26	1 1344	1.1345	1.1345
Supplies	49.34	79.76	79 76	.1140	.1256	.1256
Expenses	84.06	128 53	128.53	.1942	2025	.2025
Gross Total	624 36	928.55	928.55	1.4426	1.4626	1.4626
Back Freight Credit	184 70	205.00	205.00	.4268	.3229	.3229
Net Total	439 66	723 55	723.55	1.0158	1.1397	1.1397
Tons Concentrates Trammed	432.00	634.860	634.860	Cost per ton Crude Ore .0761	0598	.0598

	Period	Month
Tons Concentrates trammed	634.8600	634.8600
Tons backfreight trammed	51.2500	51.2500
Total Tonnage Trammed	686 1100	686.1100

shows "Back Freight Credit" This is for freight hauled from the railroad to the mill over the tram and is credited to the operating costs of the tram This amount credited here is charged to the mill or mine, as the case may be, as a freight charge as it would be in case it was hauled by truck For example, the "Gross Total" money for the period, shown in Table 8, line 4, was $928 55 From this deduct the back freight credit of $205 00 leaving $723 55 for a net total cost of operating the tram for the period.

Table 9 is a summary of Tables 1 to 8 for the period February 1 to 8, 1930. The "Total Money" for "Breaking Ground" includes the cost of development.

Table 9. Hypothetical Mining Company. Approximate Cost Data.

Summary

Period: Feb 1 to 8, 1930 **Date:** Feb. 14, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Breaking Ground						
A Ore Body	11198.96	9883.65	9883.65	2.2904	1.3465	1.3465
B Ore Body		5038.18	5038.18		2.6064	2.6064
C Ore Body		2888.01	2888.01		.8886	.8886
Total Breaking Ground	11198.96	17809.84	17809.84	2.2904	1.4222	1.4222
Producing Ore						
A Ore Body	4038.72	4954.21	4954.21	.6908	.5648	.5648
B Ore Body		993.91	993.91		.4212	.4212
C Ore Body		982.25	982.25		1.2740	1.2740
Total Producing Ore	4038.72	6930.37	6930.37	.6908	.5822	.5822
Total Mining	15237.68	24740.21	24740.21	2.9812	2.0044	2.0044
Mill Operating	5116.61	5690.90	5690.90	.8963	.4435	.4435
Tram Operating	439.66	723.55	723.55	.0761	.0598	.0598
Total Cost Ore Milled	20793.95	31154.66	31154.66	3.9536	2.5077	2.5077

Total Tons Ore Broken .12523 12523

Total Tons Ore Produced 11903 11903

Total Tons Ore Milled ...13093 wet tons (2% moisture) or
12831 dry tons

Table 10. Hypothetical Mining Company. Hypothetical Mine. Budget Statement. February 14, 1930.

Period: February 1 to 8, 1930

Credits		
Estimated receipts from sale of concentrates 672.860 tons at $70.70		$47,571.20
Debits		
Breaking Ground "A" ore body 7340 tons at 1.0294	$ 7,555.67	
Breaking Ground "B" ore body 1933 tons at 1.0504	2,030.57	
Breaking Ground "C" ore body 3250 tons at .5786	1,880.48	
Producing Ore "A" ore body 8772 tons at .5648	4,954.21	
Producing Ore "B" ore body 2360 tons at .4212	993.91	
Producing Ore "C" ore body 771 tons at 1.2740	982.25	
Milling (dry) 12831 tons at .4435	5,690.90	
Tramway 634 860 tons at 1.1397	723.55	
	24,811.54	
Cost of breaking excess of ore milled over ore broken 570 tons at 1.1694 (Cost per ton broken in stopes Dec. 31, 1929)	666 56	
Cost of producing excess of ore milled over ore produced 1190 tons at .5822. (Average cost per ton producing ore during current period)	692.82	26,170.92
		21,400.28
Cost of development		6,343.12
Estimated operating profit for period		$15,057.16

Wet tons ore milled 13093
January settlement figures used.

Table 10 is a "Budget Statement" summarizing Tables 1 to 9 for the period February 1 to 8, 1930 The credits shown are for 672 860 tons of concentrate produced as shown in Table 7 "Tons Concentrate Produced" for the period This concentrate had a value of $70 70 per ton. The value of the concentrates is taken as the average value for

the previous monthly settlements, but in case of wide fluctuation in metal prices, the very latest settlement figures should be used to be of greatest value Under "Debits," "Breaking Ground," "A" Ore body $7,555.67 is taken from Table 1 and does not include cost of development; likewise the cost of "Breaking Ground" for "B" and "C" ore bodies does not include development cost. The figures for "Producing Ore" in the three ore bodies and the cost of milling and tram costs are taken from Table 9. The next item in Table 10 is "Cost of breaking excess of ore milled over ore broken—570 tons—$666 56 It will be seen in Table 9 that the total tons of ore broken was 12,523 and in Table 10 the wet tons milled was 13,093 or 570 tons in excess of ground broken in stopes. It will also be seen in Table 9 that the total tons produced for this period was 11,903 and as there were 13,3093 wet tons milled there was an excess of 1,190 tons milled over ore produced This 1,190 tons at $0 5822 gives a debit of $692 82 shown in Table 10. The cost of development is deducted from the estimated profit for the period.

Table 11 is a summary or condensation of costs from February 1 to 8, 1930 and the information is taken from Table 10.

Table 11. Hypothetical Mining Company. Hypothetical Mine. February 14, 1930

Summary February 1 to 8, 1930

Credits		
Estimated receipts from sale of concentrates Feb 1 to 8		$47,571.20
Debits		
Breaking, Producing, Milling & Tramway	$24,811.54	
Cost of breaking excess of ore milled over ore broken 570 tons	666.56	
Cost of producing excess of ore milled over ore produced 1190 tons	692.82	26,170.92
		21,400.28
Cost of development		6,343.12
Estimated operating profit Feb. 1 to 8		$15,057.16

Table 12 is a summary of costs from February 1 to 15, Table 13 is a summary from February 1 to 23; and Table 14 is a summary from February 1 to 28, 1930. It will be noted that in Table 14, for the entire

Table 12. Hypothetical Mining Company. Hypothetical Mine. February 20, 1930

Summary February 1 to 15, 1930

Credits		
Estimated receipts from sale of concentrates Feb. 1 to 15		$103,513.78
Debits		
Breaking, Producing, Milling & Tramway	47,346.46	
Cost of breaking excess of ore milled over ore broken 1028 tons	1,202.15	
Cost of producing excess of ore milled over ore produced 1129 tons	660.79	19,209.40
		54,304.38
Cost of development		11,958.57
Estimated Operating profit Feb 1 to 15		$42,345.81

Table 13. Hypothetical Mining Company. Hypothetical Mine. February 28, 1930

Summary February 1 to 23, 1930

Credits		
Estimated receipts from sale of concentrates February 1 to 23		$161,935 49
Debits		
Breaking, Producing, Milling & Tramway	$68,533.45	
Cost of breaking excess of ore milled over ore broken 838 tons	979.96	
Cost of producing excess of ore milled over ore produced 1526 tons	870.60	70,384.01
		91,551.48
Cost of development		17,001.43
Estimated operating profit Feb. 1 to 23		$74,550.05

month, there were more tons of ore broken than were milled, therefore the cost of breaking this excess of 2,133 tons is deducted from the debits, while the excess of ore milled over ore produced is included with the debits.

Table. 14. Hypothetical Mining Company. Hypothetical Mine. March 13, 1930

Summary February 1 to 28, 1930

Credits		
Estimated receipts from sale of concentrates February 1 to 28, 1930		$193,110.83
Debits		
Breaking, Producing, Milling & Tramway	$87,838.38	
Cost of breaking excess of ore broken over ore milled 2133* tons	2,673 18*	
Cost of producing excess of ore milled over ore produced 691 tons	359.91	85,525.11
		107,585.72
Cost of development		19,629 56
Estimated operating profit for month of February		$87,956.16

* To be deducted from **Debits**

Table 15. Hypothetical Mining Company. Approximate Cost Data.

Mine Operating—Breaking Ground "A" Ore Body

Period: Feb. 24 to 28, 1930 **Date:** March 13, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor	2448.40	1985.59	9928.95	.3222	.2569	.3030
Supplies	1410.37	693.33	4512.39	.1856	.0897	.1377
Expenses	2321 49	939.20	8220.92	.3055	.1216	.2509
Total	6180.26	3618.12	22662.26	.8133	.4682	.6916
Developm't	1310.07	2068.63	8584.27	.1724	.2677	.2620
Total Cost	7490.33	5686.75	31246.53	.9857	.7359	.9536
Tons Ore Broken	7599	7728	32764			

The figures given for the first three periods of the month are approximations and may be too high or too low, and a final adjustment is made in the last period of each month. In case an overcharge is made during the first three periods for any item, such as development, making the total greater than for the entire month, the amount

Table 16. Hypothetical Mining Company. Approximate Cost Data.

Mine Operating—Breaking Ground "C" Ore Body

Period: Feb 16 to 23, 1930 **Date:** Feb 28, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor	817.97	726.13	2238 43	0.4344	0.5646	0.4144
Supplies	513 68	399.25	1415.64	.2728	.3105	.2620
Expenses	810.25	413.93	1482.63	.4303	.3219	.2745
Total	2141 90	1539 31	5136.70	1.1375	1.1970	.9509
Developm't	981.24	819.80	2512.18	.5211	.6375	.4650
Total Cost	3123.14	2359.11	7648.88	1.6586	1.8345	1.4159
Tons ore	1883	1286	5402			

Table 17. Hypothetical Mining Company. Approximate Cost Data.

Mine Operating—Breaking Ground. "C" Ore Body

Period: Feb 24 to 28, 1930 **Date:** March 13, 1930

Operations	Total Money			Cost per Ton Crude Ore		
	Average Period	Period	Cumulative for Month	Average Period	Period	Cumulative for Month
Labor	715.46	987 49	3225.92	.4344	.9110	.4974
Supplies	449.30	233 17	1648.81	.2728	.2151	.2542
Expenses	708.70	580.12	2062.75	.4303	.5351	.3180
Total	1873.46	1800.78	6937.48	1.1375	1 6612	1.0696
Developm't	858.25	557.44*	1954.74	.5211	.5142*	.3014
Total Cost	2731.71	1243.34	8892.22	1.6586	1.1470	1.3710
Tons Ore Broken	1647	1084	6486			

* This is to be deducted to take care of an overcharge in the first three periods of the month.

necessary to adjust this is shown in red in the proper place in the fourth period and this deducted from the cumulative for the month. This is illustrated in Tables 16 and 17. Note that in Table 16 the cost of development, cumulative for the month (from February 1 to 23), is shown as $2512.18. After the final correct costs for the month were determined it was found that this figure was too high. In Table 17 note that the cumulative for development for the whole month was $1954 74 or $557 44 less than was shown in Table 16 for the first three periods This $557 44 is shown in red in the cost for the period and is deducted from the total cost.

To summarize this method of compiling approximate cost data: Aproximate costs are kept for periods of about eight days each The operations at a mining property are divided into subdivisions such as "Breaking Ground"; "Producing Ore", "Milling Ore", and "Transportation of the Concentrates" The basis for determining these costs is: "Labor," "Supplies," and "Expenses" Labor costs are obtained from the payroll, costs of supplies are obtained from warehouse records, and "Expenses" include such items as power, liability insurance and laboratories Along with the current costs are shown the average costs during the previous six months period so that the operator may have a basis for comparison The value of the metal produced is shown and the profits for the period are approximated If the costs for any operation are too high the operator will know it before this condition has continued long. The executive in charge of mines a long distance away can keep in close touch with the costs at each property.

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SECOND PROGRESS REPORT

THE DEVELOPMENT OF AN

Electro-Hydrometallurgical Process for Copper Flotation Concentrate

by

Carl Frederick Floe

and

Arthur Eilert Drucker

School of Mines and Geology

ENGINEERING BULLETIN NO. 38

ENGINEERING EXPERIMENT STATION

H V Carpenter, Director

Published January, 1932

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc

Bulletins are available as listed on pages 45 and 46.

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The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

Development of an Electro-Hydrometallurgical Process for Copper Flotation Concentrate

Second Progress Report[1]

by

Carl Frederick Floe and Arthur Eilert Drucker

INTRODUCTION

About nineteen months ago the First Progress Report on this process for producing electrolytic copper from flotation concentrate by a hydrometallurgical method, was published by the Engineering Experiment Station of the State College of Washington Since that time the work has been continued in greater detail and on a somewhat larger scale, using improved equipment This paper presents the results of this later experimental work

Interest in the electro-hydrometallurgy of copper sulphides (mill concentrate) has increased greatly in the last two years Predictions that this would be true were made nearly fifteen years ago, although little or no experimental data were available at that time, and even at present the supply is meager[2] Actual experimental work on this problem was started in our laboratories in February 1927, and the first progress report published in April 1930[3]

The results published in the former report indicated that the most successful way of recovering the copper from a sulphide concentrate would involve oxidizing roasting, followed by leaching with dilute sulphuric acid, and electrolysis of the resulting solution, using insoluble lead anodes and copper sheet cathodes The object of the experiments that have been conducted since that time has been:

1 To obtain more data on the conditions necessary for successful roasting in order that a high extraction of the copper can be made

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[1] Second Progress Report completed January, 1932

[2] A E. Drucker, "Hydrometallurgy of Copper Sulphides" Mining and Scientific Press. Nov. 17, 1917.

[3] A E. Drucker and C. F Floe, "Development of An Electro-Hydrometallurgical Process for Copper Flotation Concentrate." The State College of Washington, Engineering Experiment Station Bulletin No 35 April 1930.

2. To determine what impurities will collect in the solutions when they are used repeatedly, and the effect of these impurities on electrolysis.

3. If impurities do collect in the solution, to find a suitable way of overcoming their deleterious effects.

4. To determine some of the characteristics of the electrolysis of acid copper sulphate solutions containing ferric and ferrous iron

5. To determine if it is economically possible to recover the precious metal from the tailing

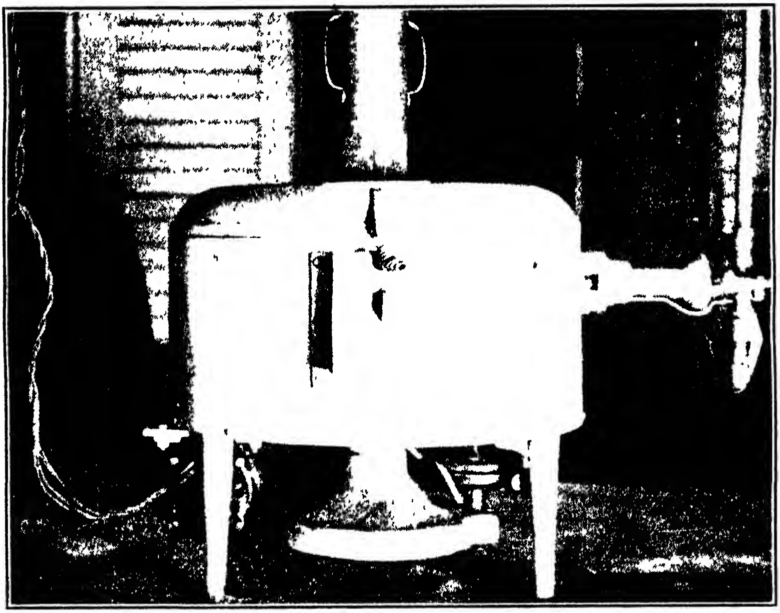

Figure 1 Laboratory Roasting Unit.

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ledgement should be made to Dr. G. D Van Arsdale, Consulting Metallurgist; William Wraith, Vice-president of the Inspiration Consolidated and the Andes Copper Mining Company; and R L Forcum, Chief Chemist of the Roan Antelope Copper Mines, Ltd Further acknowledgement is made to the Utah Copper Co and the Index Copper Co, who kindly furnished the concentrates used in this work, and to C J Durway, graduate assistant, who performed much of the analytical work in connection with the treatment of the copper leached residues for the recovery of the gold and silver.

EQUIPMENT USED IN EXPERIMENTAL WORK

Roasting:

The furnace in which all roasting tests were made is shown in Figure 1 It is a Nicholas Herreshoff laboratory roasting unit consisting of a thirteen-inch iron hearth suitably insulated with fire brick Stirring of the charge is effected by means of a rabble arm turned by a gear mechanism connected to a small electric motor The average speed of the rabble arm is about three revolutions per minute The furnace is fired by means of a gas burner shown on the right hand side; Flamo gas, supplied by the Standard Oil Company, being used for fuel By carefully regulating the supply of gas, the temperature of the furnace could be controlled quite closely However, it is believed that the temperature control was no more exact than could be obtained in the present day commercial types of roasting furnaces

The amount of air admitted to the roast could be partially regulated by means of the door in front, and also by a damper in the flue During most of the tests a charge of from 1500 grams to 2000 grams of concentrate was used

Discharge of the furnace, after the roast was complete, was effected by removing a plug in the bottom of the hearth, and allowing the charge to rabble out In this way material held up in the corners and insufficiently roasted was allowed to remain behind.

Leaching:

Two different series of leaching tests were conducted The first of these, which will be called the Large Scale Laboratory Leaching Tests, was made in the experimental leaching plant shown in Figure

2. This consists of two series of two-liter bottle agitators and several settling cones. The latter were used for thickening the solids and decanting off the clear liquid solution prior to electrolysis. The thickened solids were run through a filter press (Figure 3) and washed before drying. In the bottle agitators the solids were kept in suspension by means of compressed air which entered through a jet at the neck of each of the inverted bottles. The compressed air necessary for agitation was supplied by the air compressor shown in Figure 4

Figure 2 Experimental leaching unit used for large scale laboratory leaching tests

Small scale leaching tests were made in the apparatus shown in Figure 5 This consists of a two and one-half liter jar in which is inserted a large glass stirring rod The end of this rod is connected to a pulley which is rapidly turned by means of a small electric motor The solutions could be heated during leaching to any desired temperature by means of a Hotpoint immersion type heater

Electrolysis:

The electrolysis of the solutions from the large scale leaching tests was made in the cells shown in Figure 6 The three cells were arranged in cascade, and a continuous circulation of the electrolyte

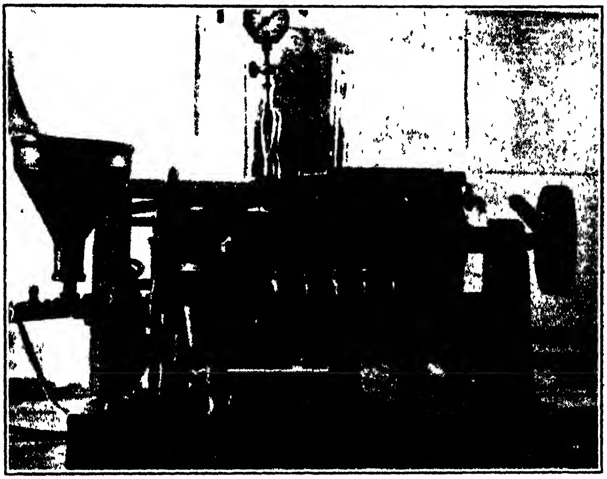

Figure 3 Filter press used for clarifying solutions prior to electrolysis

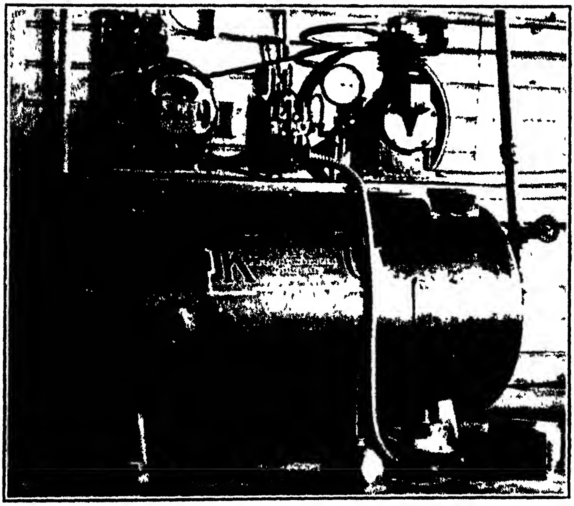

Figure 4 Air compressor supplying compressed air for the leaching plant shown in Figure 2 .

maintained by means of an air lift from the lower to the upper cell. Sheet lead anodes and copper sheet cathodes were used. Current for the electrolysis was supplied by a motor generator set having a capacity of 100 amperes at six volts. The amount of current could be controlled by means of a field rheostat mounted above the generator

The apparatus for the electrolysis of the solutions from the small scale leaching tests is shown in Figure 5. This consists of a two liter cell containing two copper sheet cathodes and three lead anodes Current was supplied by the small motor generator set shown on the left ,the amount being regulated by a slide wire rheostat. Circulation of the electrolyte was maintained by two glass stirring rods attached to mechanical spinners.

Analytical Methods and Calculations

In general all analyses were made by the standard methods Copper was determined by the iodide method, and iron by the permanganate method An outline of the procedure followed in the determination of acidity, ferrous iron, and total iron, may be found in Keffer's "Methods in Non Ferrous Metallurgical Analysis"[1]

In some of the tables a quantity called "acid soluble iron" has been given This was determined by leaching 0.5 gram of the roasted calcine with 30 cc of a 5% solution of sulphuric acid, filtering, and determining the total amount of iron which had dissolved Determinations of acid soluble copper were made in the same way This offered a rapid method of determining the degree of completion of a roast, and how successful it had been

In most cases the analytical results check quite closely, and considerable care was taken to make them do so, especially in the small scale tests where the solution volumes could be controlled within narrow limits.

During the tests it was found to be more expeditious to calculate the various weights on the basis of analytical results. For example, in roasting it was not practical to remove the entire charge from the furnace when the roast was complete, because certain portions would be held in the corners of the hearth and would be insufficiently

[1] McGraw-Hill Book Company, 370 Seventh Avenue, New York, N. Y.

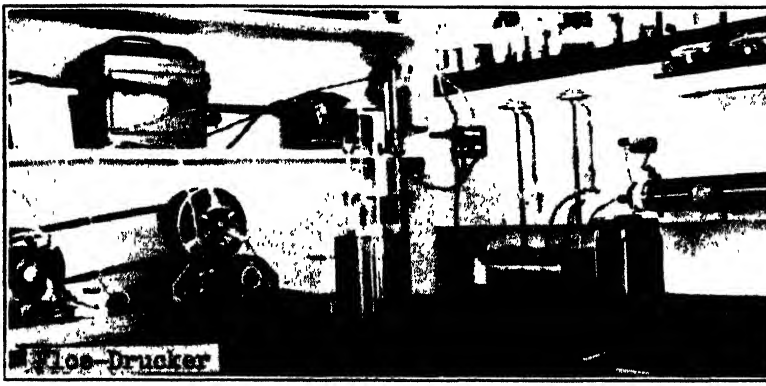

Figure 5 Equipment used for small scale leaching and electrolysis

Figure 6. Apparatus used for the electrolysis of the solutions from the large scale leaching tests An end view of the leaching apparatus is shown in the background

roasted. For this reason only the part of the charge which had circulated freely was removed, and the increase in weight, during roasting, was determined by the decrease in the amount of iron and copper in the calcine over that in the original concentrate. In like manner the weight of leached residues was usually calculated on the basis of the change in the iron assay.

All calculations in the tables have been made by slide rule, the accuracy of which should be within the limits of the analytical methods.

Nature of Concentrate Used for Experimental Work

Two different concentrates were used in these tests. The first was from the flotation mill of the Index Copper Company at Index, Washington, and consisted essentially of chalcopyrite with a few per

Table 1. Screen Analyses of Index and Utah Concentrate

Mesh	Index Concentrate				Utah Concentrate			
	Weight	%	Total % on	Total % passing	Weight	%	Total % on	Total % passing
+28	5 g.	0.5	0.5	99.5				
35	5	0.5	1.0	99.0				
48	7	0.7	1.7	98.3				
65	23	2.3	4.0	96 0	0 g.	0.0	0.0	100.0
100	108	10.8	14.8	85.2	5	0.5	0.5	99.5
150	157	15.7	30.5	69.5	23	2.3	2.8	97.2
200	148	14.8	45.3	54.7	99	9.9	12.7	87.3
—200	547	54.7	100.0	0.0	873	87.3	100.0	0.0

N. B. Dusting losses added to undersize of finest screen.

Table 2. Quantitative Analyses of Index and Utah Concentrate

	Index Concentrate	Utah Concentrate
	Per cent	Per cent
Copper	29.2	32.9
Iron	24.8	28.0
Sulphur	26.1	32.5
Gold	Trace	0.18 oz./T.
Silver	3.1 oz./T.	2.1 oz./T.

cent of bornite. A microscopic examination also revealed the presence of some quartz, although the material was fairly clean. The second concentrate came from the Magna mill of the Utah Copper Company, and was an exceptionally clean chalcopyrite flotation concentrate, containing a small amount of bornite A screen analysis of the two concentrates is given in Table 1 and a quantitative analysis in Table 2.

RESULTS OF EXPERIMENTAL WORK

1. Roasting Tests

Method of Conducting Roasts:

In all roasting tests a charge of from 1500 to 2000 grams of concentrate was used After much preliminary testing, some of the reresults of which were included in the former report, it was found that the following method of conducting the roasts gave the best results, that is, it produced the greatest amount of soluble copper with the least amount of soluble iron

The concentrate was first placed in the furnace and the gas flame turned on until the temperature of the charge was brought up to the ignition temperatures of the sulphides This has been determined to be about 325° C for pyrite and 430° C for Cu_2S[2] The flame was now turned off completely and the sulphur allowed to burn The burning of the sulphur liberates sufficient heat to maintain the entire charge at a red heat for a period of from one to two hours This completes the first stage of the roasting operation

After the temperature had decreased again, and the sulphur content of the calcine was reduced to about 9 to 12 %, the flame was again turned on and the muffle temperature brought up to a low red heat, or about 550° C The temperature was held at this point until there was no longer any indication that SO_2 was being formed This comprises the second stage of roasting

During the third and final stage, the muffle temperature was raised to about 625° C to 675° C, and roasting continued for several hours in order to convert as much of the iron as possible into insoluble ferric oxide, and to insure the complete decomposition of the sulphides.

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[2] H. O. Hofman, "General Metallurgy." McGraw Hill Book Company

Table 3. Progress of Roasting Index Concentrate. Sample No. 1 Taken at the End of 1 Hour of Roasting; No. 2 at the End of 2 Hours, etc.

Sample	Original Concentrate	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
	%	%	%	%	%	%	%	%
Total Copper	29.2	29.0	28.4	27.4	26.6	26.6	26.6	27.5
Water Soluble Copper	0.0	2.6	7.2	6.4	6.5	5.2	5.0	4.6
Acid Soluble Copper	0.0	6.9	20.6	25.9	25.4	26.4	26.5	26.5
Total Iron	24.8	24.7	24.2	23.5	23.0	23.0	23.2	24.0
Water Soluble Iron	0.0	0.4	0.5	0.4	0.5	0.4	0.3	0.2
Acid Soluble Iron	0.0	13.6	10.2	3.3	3.2	2.4	2.2	2.0
Total Sulphur	26.1	15.3	8.7	7.6	7.4	7.2	6.9	6.0
Water Soluble Sulphur	0.0	1.7	5.3	4.8	5.1	4.3	4.1	3.4

Table 4. Progress of Roasting Utah Concentrate. Samples Taken at End of Hours of Roasting Indicated at Top of Column.

Sample	Original Concentrate	½ hr	1 hr	2 hrs	3 hrs	4 hrs	6 hrs	8 hrs	10 hrs
	%	%	%	%	%	%	%	%	%
Total Copper	32.9	32.7	32.5	31.8	30.8	30.6	30.6	30.4	32.0
Acid Soluble Cu.	0.0	10.4	21.7	27.1	28.4	29.6	30.4	30.2	31.2
Water Soluble Cu.	0.0	1.3	7.7	12.7	11.9	11.3	9.8	8.6	0.8
Total Iron	28.0	27.9	27.7	27.0	26.2	26.0	25.9	25.5	26.9
Acid Soluble Fe.	0.0	13.1	14.8	10.1	7.1	6.0	5.7	4.2	2.3
Water Soluble Fe.	0.0	0.4	1.5	1.0	0.6	0.7	0.7	0.7	0.3
Total Sulphur	32.5	23.0	13.5	11.6	11.4	10.3	10.0	8.4	6.0

This method of roasting has been found to be very effective in giving the maximum solubility of the copper. Two points are of particular importance, the first being that the initial temperature of the muffle should not be far above the ignition temperature of the sulphides or overheating may result, and the second that the final temperature should not be so high that insoluble ferrates of copper

and iron are formed It was found that this occurred if the temperature exceeded about 670° C

Results of Tests:

Table No. 3 and Table No 4 show the progress of the roasting of Index and Utah concentrate respectively by the method just described In these tests samples were taken at the end of the time intervals indicated, and each sample analyzed in order to determine how far the roast had proceeded.

Figures No. 7 to 12 inclusive show graphically the results given in Tables 3 and 4 Figures No 7 and 8 indicate how the sulphur is eliminated as the roast progresses, the greatest portion being expelled during the first stage. During the second stage the rate is retarded very rapidly, and in the last stage it again increases, due to the increase in temperature to a point in excess of the decomposition temperature of the sulphates That is, for copper sulphate about 653° C:

$$2\ CuSO_4 = CuO\ CuSO_4 + SO_3$$

Figures No 9 and 10 show the nature of the products formed during the roasting of Index concentrate In Figure 9 the per cent acid soluble and water soluble copper, and acid soluble and water soluble iron in the calcine have been plotted against the time of roasting in hours Figure 10 is the same except that the per cent of sulphur remaining in the calcine has been used as abcissae which gives a smoother curve By acid soluble iron and copper is meant the amount that is soluble in a 5% solution of sulphuric acid.

The curve for acid soluble copper goes up very rapidly at first, and is then retarded during the second stage of the roast as the reaction nears completion The solubility of the copper decreases during the final stage due to slight overheating and consequent formation of insoluble ferrate The acid soluble iron is shown to increase very rapidly at first; more rapidly than the copper, indicating that the iron roasts somewhat ahead of the copper It then decreases very rapidly when the temperature becomes sufficiently high to promote the rapid formation of insoluble Fe_2O_3 The water soluble copper forms quite rapidly at first, remains fairly constant during the second stage of the roast, and then decreases as the temperature is raised to a point in excess of the decomposition temperature of $CuSO_4$ (653° C). The

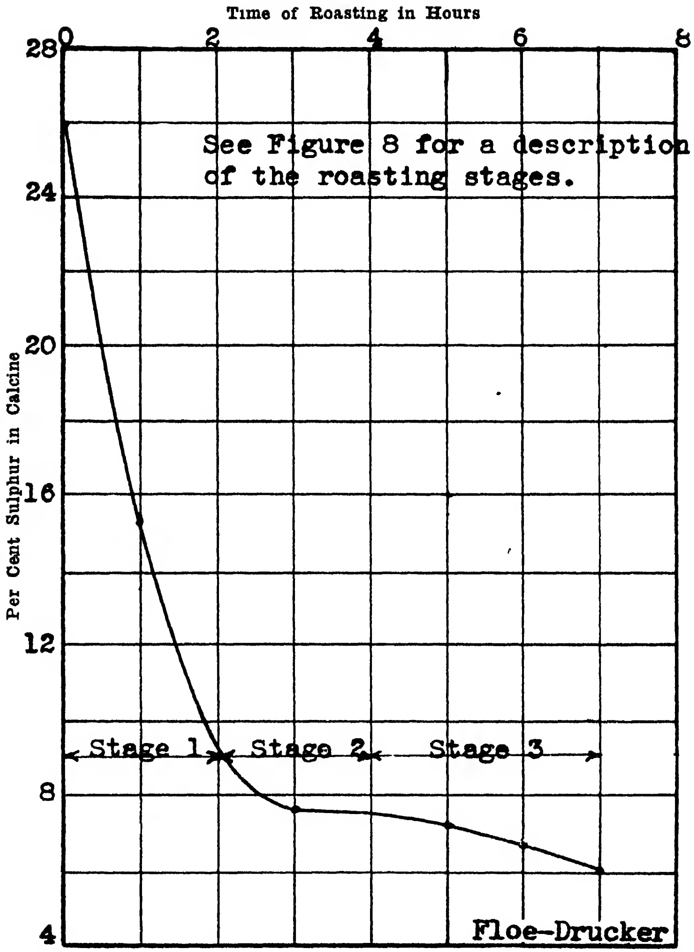

Figure 7 Elimination of sulphur during the roasting of Index Concentrate.

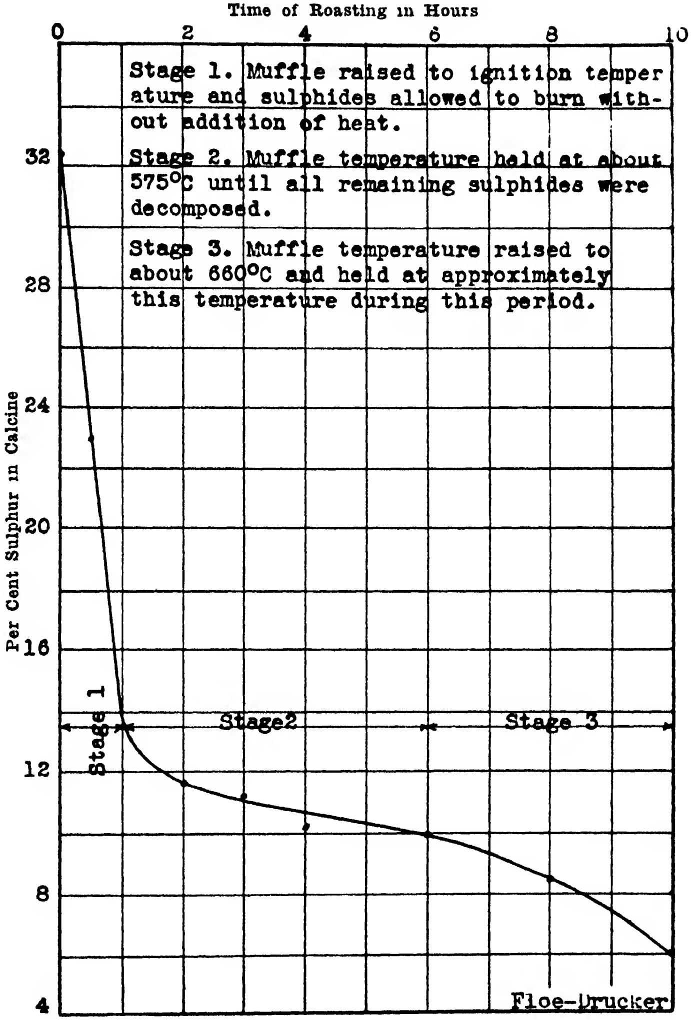

Figure 8 Elimination of sulphur during the roasting of Utah Concentrate.

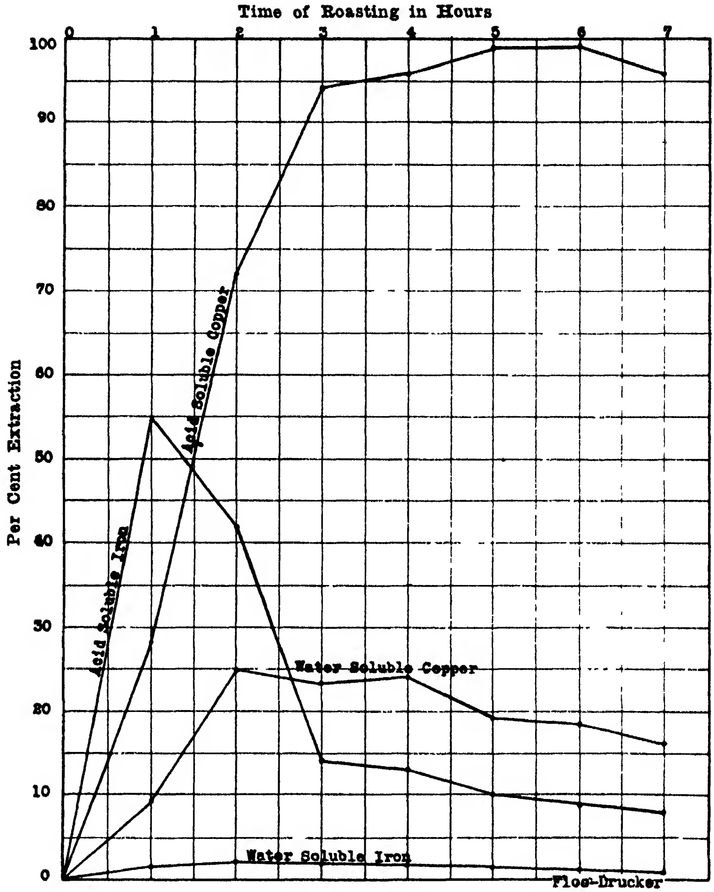

Figure 9 Curves showing the nature of the products formed during the progress of roasting Index Concentrate

amount of water soluble iron is not great at any time, indicating that the sulphates of iron are decomposed, with the formation of copper sulphate, almost as rapidly as they are formed.

Figures 11 and 12 show the nature of the products formed during the roasting of Utah concentrate These curves are very similar to those of Figures 9 and 10, which is to be expected, since the roasts were conducted in the same manner.

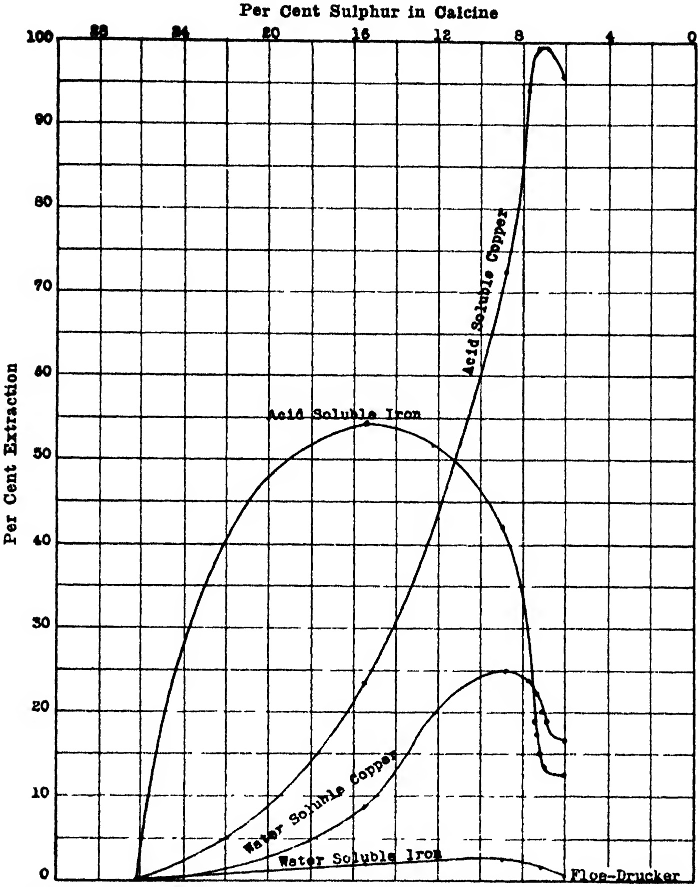

Figure 10 Curves showing the nature of the products formed, as sulphur is eliminated during the progress of roasting Index Concentrate

The appearance of the calcine during the progress of the roast undergoes several changes as the various products are formed. During the first stage it changes from the color of chalcopyrite to a dark gray black color, and a microscopic examination reveals that a great portion of the iron is now in the form of the magnetic oxide The curves of Figures 9, 10, 11, and 12 show that it is during this period that the greatest amount of soluble iron is formed At the same time the soluble copper is increasing rapidly, or in other words, the copper

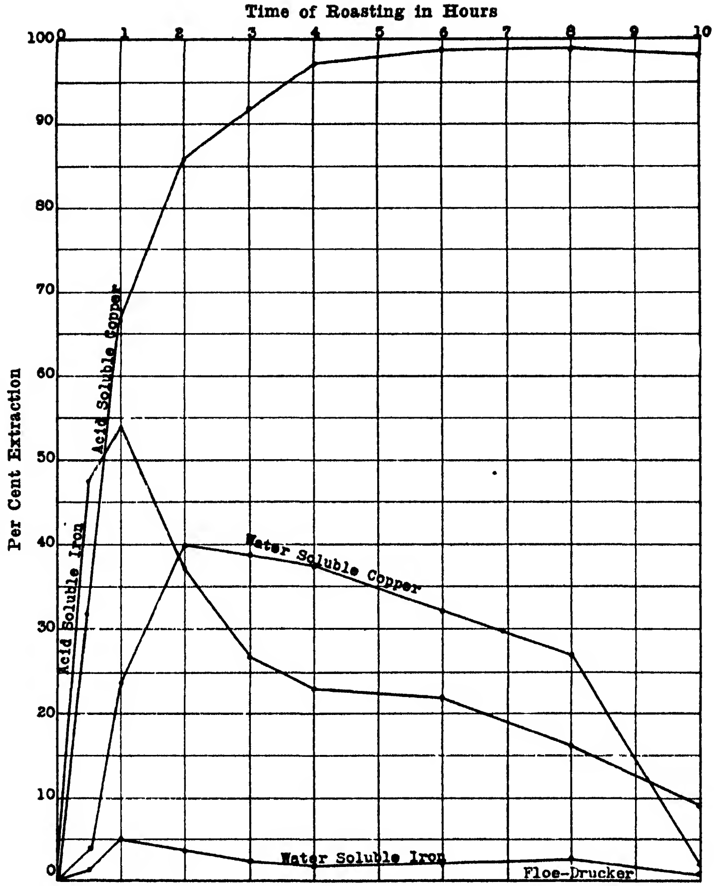

Figure 11. Curves showing the nature of the products formed during the progress of roasting Utah Concentrate.

is being converted into CuO and $CuSO_4$ and the iron into FeO and Fe_3O_4 with a small amount of $Fe_2(SO_4)_3$ and $FeSO_4$.

The amount of $CuSO_4$ formed depends upon several variable factors such as temperature, air supply, rate of rabbling and particle size. It will be directly dependent upon the partial pressure of the SO_3 gas in contact with the calcine The formation of this latter compound by the oxidation of SO_2 according to the reaction $SO_2+\frac{1}{2}O_2=SO_3$, is greatly assisted by the catalytic action of certain of the solid sur-

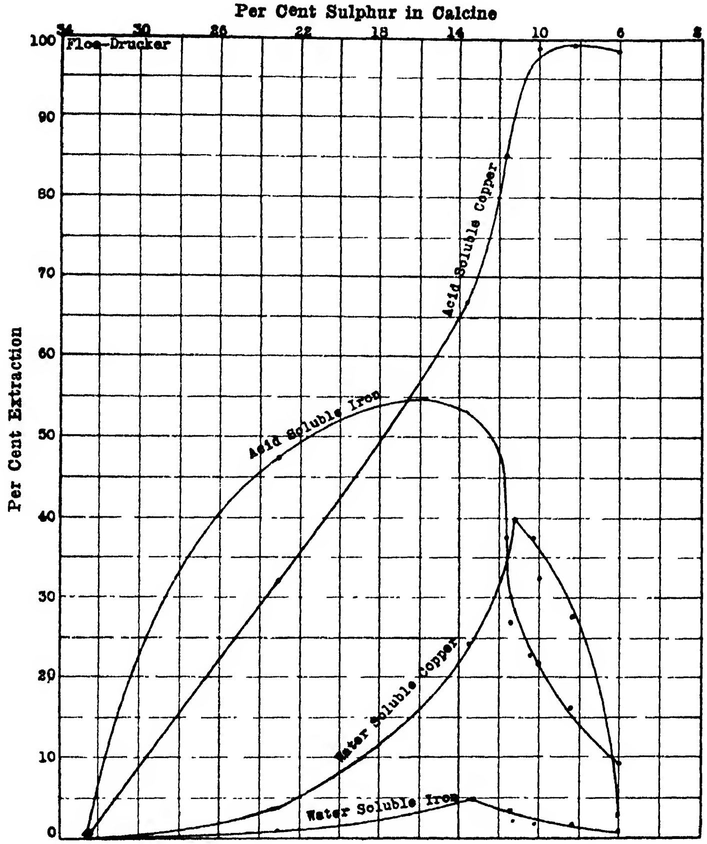

Figure 12 Curves showing the nature of the products formed, as sulphur is eliminated during the progress of roasting Utah Concentrate

faces. Iron oxide and silica are known to have this effect; especially when in a finely divided state and in the presence of an excess of air[3] The presence of FeS also greatly assists the formation of $CuSO_4$[4] A considerable difference in the total amount of $CuSO_4$ formed in the first stage of roasting Index and Utah concentrate can be noted, which can be ascribed to differences in some of these variable factors

[3] "General Metallurgy," by H O. Hofman, McGraw Hill Book Co, 1913.

[4] "Metallurgy of Copper," by Hofman and Hayward, McGraw Hill Book Company, 1924

During the second stage of the roast the concentrate changes from a gray black color to a brick red, due to conversion of the Fe_3O_4 into Fe_2O_3. Even after completing the roast, however, there are some magnetic particles present, so that this reaction is not complete. This accounts for the fact that a small percentage of the iron is still soluble. The existence of some FeO is still quite likely, and later tests indicate that approximately 50% of the soluble iron is in this form

During the last stage of the roast the color does not change appreciably unless overheating is allowed to take place, which darkens it rapidly again due to the formation of ferrates The best roasts, or those containing the greatest amount of soluble copper, were of a brick red color

It was found that the ferrate was formed if the temperature exceeded about 670° C, and not 650° C as was previously supposed This is illustrated by the curve for water soluble copper in Figure 11, where during the last stage of roasting, the amount of $CuSO_4$ decreased to about 2% To do this the temperature must have exceeded 653° C in order that the sulphate could break down into the basic sulphate:

$$2\ CuSO_4 = CuO.CuSO_4 + SO_3$$

At the same time, however, the amount of total soluble copper did not decrease, which shows that no ferrate was formed This offers one means of partially controlling the amount of copper sulphate in the final calcine. It cannot be fully controlled, however, because the temperatures can never be allowed to go so high that the basic sulphate is decomposed (about 700° C) The control of the amount of sulphate present in the roast is important, because it is this that determines the amount of excess acid that will be regenerated during electrolysis

Table 5 (see insert) gives the results obtained from the analyses of different roasts In Nos 1 to 7 inclusive, Index concentrate was used, while in No. 8 and 9, Utah concentrate was used. In all cases the roasts were conducted in the manner previously described, that is, in three stages. The temperatures given in column 6 represent the maximum finishing temperature only. The amount of water soluble and acid soluble material in each roast was determined in most cases by leaching a

25 gram sample for a period of three hours at about 40° C., and analyzing the resulting solution and residue The solution from the acid leach contained about 4% free H_2SO_4 when leaching was complete.

Somewhat ideal results were obtained in Roast No. 1 in that a large portion of the copper was converted into the soluble form. The amount of soluble iron would probably have been decreased if the roasting had been continued for a longer period. The calcine from this roast was a full brick color and a microscopic examination failed to reveal any undecomposed sulphides and few magnetic particles.

The analysis of Roast No. 2 indicates that the finishing temperature was not high enough Although the copper extraction is fairly high, the tailing runs 2% sulphur, showing that there are still undecomposed sulphides present The amount of water soluble copper sulphate could also be reduced by a higher finishing temperature At the same time the amount of soluble iron should be reduced

Roast No 3 is similar to No 1 In No 4 the finishing temperature was sufficiently high to decompose much of the cupric sulphate. However, there is still considerable copper present in the form of the basic sulphate as shown by the high sulphur content of the water leach tailing The extraction of copper is good, despite the high temperature, and all but a small percentage of the iron is insoluble. This again shows that it is possible to roast at a temperature high enough to decompose copper sulphate, but the temperature must be controlled very closely or there is danger of forming ferrates This is illustrated by Roast No. 5 where the temperature was allowed to go to 700° C for a brief period, with the result that the extraction of copper decreased considerably

Roast No. 6 has been greatly overheated, resulting in the formation of considerable ferrate. The overheating took place during the first stage of the roast That is, the initial temperature of the muffle was too far above the ignition temperature of the sulphides and their oxidation took place so rapidly that overheating resulted.

Roast No. 7 is included in order to show the effect of not roasting for a sufficient length of time The greater part of the copper is soluble and considerable $CuSO_4$ has been formed, but the tailing is high in undecomposed sulphides as indicated by the high sulphur

content. The formation of ferric oxide is not complete and a large part of the iron is still soluble This is also true of Roast No. 8 which was continued for a sufficient length of time, but at too low a temperature to convert all of the iron into ferric oxide. The copper compounds, however, are soluble.

Roast No. 9 is the same as No. 8, except that the calcine has been returned to the furnace and heated for three additional hours at 670° C. The result is that the copper sulphate has been almost entirely decomposed with the formation of basic copper sulphate There is still considerable soluble iron, showing that the transformation to the insoluble form is quite slow at this temperature

The analytical results in all of these tests check very well, although there are discrepancies in several cases.

All roasting tests show that there is an increase in weight of the calcine over the weight of the original charge, the amount of increase varying with the different conditions of roasting The reason for this can be illustrated by the following equation representing the principal roasting reactions:

$$2\,CuFeS_2 + 7O_2 = CuO + CuSO_4 + Fe_2O_3 + 3\,SO_2$$
$$2(184) \qquad = 80 + 160 + 160$$

The total weight of solids therefore increases from 368 units to 400 units, or a 2000 gram sample would increase to 2,175 grams This is assuming that 50% of the copper is in the form of sulphate If less sulphate is formed there will be a correspondingly smaller increase in weight The increase will also be changed if any of the iron exists in another form, and if other compounds are present that are not accounted for in the above reaction

Heat Evolved During Roasting of Chalcopyrite, and Heat Control of Furnace.

In roasting for leaching purposes the ideal result is attained if all of the copper is converted into a form that is soluble in dilute acid, and at the same time all the iron is made insoluble. The total reaction involved in doing this may be summed up as follows:

$$2\,CuFeS_2 = Cu_2S + 2\,FeS + S$$
$$Cu_2S + 2\,FeS + S + 7O_2 = CuO + CuSO_4 + Fe_2O_3 + 3\,SO_2$$

$$20{,}300 + 2(24{,}000) + 0 + 0 = 37{,}700 + 181{,}700 + 197{,}700 + 3(69{,}260)$$

Therefore

$$-\Delta H = 556{,}580 \text{ calories.}$$

or 278,290 calories are liberated from the roasting of 1 gram molecular weight of chalcopyrite at about 18° C. Since the reactions actually take place at higher temperatures this quantity is not exact, but it is sufficiently close for our purposes. The exact values would differ from the one given by the difference in heat capacities of the reactants and products

The actual heat evolved in a roasting operation of this kind would also differ from the value given, because the reaction assumed in this calculation is an ideal one Furthermore it was assumed that 50% of the copper in the roasted product exists as oxide and 50% as sulphate With the ordinary roast, where the calcine contains about 8% sulphur, this will be approximately true, although it is of course a variable quantity. This does not mean that the average roast will contain 50% of water soluble copper sulphate, because considerable of the sulphate radical in any roast will exist as basic sulphate which is not water soluble As the amount of sulphur in the calcine decreases the amount of sulphate radical will decrease accordingly, which will of course also change the heat evolved

The 278,290 calories of heat evolved per gram molecular weight of chalcopyrite is equivalent to 1515 calories per gram of chalcopyrite Considering that the concentrate is 90% pure this would be 1364 calories evolved per gram of concentrate. Under ordinary circumstances this would be sufficient to make the concentrate self roasting in present day multiple hearth roasting furnaces, if it were not for the fact that the roast must be conducted within certain temperature limits, as previously discussed, in order to produce a soluble calcine. Any effort to conserve the heat, the most of which is liberated in the early stages of the roast, (see Figures 7 and 8) would result in over-heating. In fact, it may be necessary to install some method of cooling in the first hearths of the furnace in order to prevent this, and also to devise a means of preventing too rapid oxidation of the material as it drops from one hearth to the next On the other hand it will probably be necessary to supply heat to the lower hearths, because the reactions which are taking place during this stage of the

roast do not evolve much heat; many of them, such as the decomposition of $CuSO_4$, actually being endothermic.

During the laboratory tests it was not found necessary to use any method of cooling in order to prevent overheating. Observations of the roast during the most intense liberation of heat showed the calcine to be of a dark red color, or about 600° C to 625° C. Addicks[5] states that in small scale laboratory roasting of sulphides it is practically impossible to prevent overheating, due to the rapid oxidation of the sulphur. However, no trouble at all was experienced in this way, despite the fact that the concentrates used were of higher grade than those used by him That is, they were higher in copper However, his concentrates contained a great deal of iron pyrite so that the total sulphur content was about the same Pyrite loses sulphur somewhat more rapidly than chalcopyrite, and it is possible that this is the reason that overheating resulted in his laboratory experiments With the present knowledge of selective flotation there are few copper concentrates that contain much pyrite, so that this difficulty need no longer be troublesome.

2. Leaching Tests

Small Scale Tests:

Small scale leaching tests were carried out by using 400 grams of roasted calcine and about 1800 to 2000 cc of solution in the apparatus previously described. The first of these, the results of which are given in Table No 6, were designed to show how the iron would build up in the solution by using it repeatedly if no attempts were made to purify it. In these tests the volume was kept constant at 1800 cc, evaporation losses being made up for by the addition of water. No solution was discarded between leaches, the excess of acid regenerated by electrolysis being neutralized by the addition of calcium oxide. The results show that while the iron in the solution increases slowly with each leach, it does not increase as fast as would be expected from the analysis of the amount of acid soluble iron in the calcine This acid soluble iron was determined by the method described under "Analytical Methods," and would indicate that there would be an increase of 8 4 ÷ 1.8 or 4.7 grams of iron per liter during

[5] Possibilities in the Wet Treatment of Copper Concentrates," by Lawrence Addicks; Transactions A. I. M. E., Vol. LV, 1916.

each leach. As can be seen from the results the increase was only a fraction of this amount, showing that the solubility of the iron is much less in an acid solution containing a fairly high concentration of copper and some iron, than in one which does not contain any. This fact was noted in all the leaching tests, and has also been mentioned by Middleton[6]

Table 6. Illustration of How the Iron Content of the Leach Solutions Increases, if They Are Used Repeatedly Without Being Purified.

Leach No.	Volume of Solution	Grams Calcine Leached	Acid Soluble Fe in Calcine	Time of Leaching	Temp. of Leaching	Analyses of Leach Solution		
						Total Fe	Ferrous Fe	% H_2SO_4
1	1800 cc.	400 g.	2.1%	4 hrs.	50° C	3.0 g/l	1.8 g/l	4.1%
2	1800	400 g.	2.1	4	50	4.4	2.0	3.2
3	1800	400 g.	2.1	4	50	5.6	2.1	3.4

The results of the tests given in Table No 6 showed that the concentration of the iron would increase as the solutions were reused, and consequently it would be necessary to devise a method of getting rid of it, or it would increase to such a point that electrolytic precipitation of the copper would not be practical. To do this it was decided to try the following method of leaching as former tests had indicated that it would give good results·

1 The calcine is first leached with just enough solution that all or nearly all of the acid is neutralized At the same time MnO_2 may be added in order to oxidize the ferrous iron in the solution to the ferric state

2. Sufficient calcium oxide is now added to complete the neutralization, if necessary, and to precipitate the ferric iron This latter reaction is quite rapid after neutralization has been affected. The entire charge is now neutral leached for several hours

3 Enough more of the original solution is now placed in the agitator to build up the acidity to about 3 or 4% H_2SO_4 This has been found to be high enough to get a good extraction of the copper. Agitation is continued for one to two hours with this acid strength in order to insure the solution of all the soluble copper

[6] P. C Middleton, "Mining and Scientific Press," August 2, 1919

Results of twelve small scale leaching tests conducted in this way are given in Table 7 (see insert). In these tests the solutions were used repeatedly. That is, the solution from one leach was electrolyzed, with the deposition of copper and regeneration of the sulphuric acid solvent, and the resulting solution used as the lixiviant for the next leach. In most cases all of the solution was not reused, as it was necessary to discard a small amount after each electrolysis in order to prevent the acid concentration from becoming too high. In other words, more acid was regenerated in the electrolysis than was needed for the next leach, because of the presence of sulphate in the calcine. The amount of the discard each time is shown in the table by the difference in the total volume of the solution at the end of a leach, and the total cc of solution added to the next leach. The amount discarded was kept at a minimum by the addition of calcium oxide during leaching, which neutralized most of the excess acid In fact in some cases too much CaO was added, and it was necessary to add concentrated sulphuric acid during the last part of the leach in order to make the acidity high enough to insure solution of all the soluble copper The results indicate that the question of getting rid of the extra acid regenerated will not be a difficult one to solve, as it can be entirely neutralized with lime A small by-pass at the end of each electrolysis may also be desirable as this would keep the solution fresh.

The results given in Table 7 check very well although there are some variations Particular care was taken to keep the volume of the solutions as constant as possible in order to obtain check results, but the difficulty of doing this, due to evaporation losses, will account for some of the discrepancies Wash water was usually added to make up for evaporation losses The tails from each leach were thoroughly washed, and the wash water added to the solution in order to reduce the loss of copper as far as possible. In some cases it was necessary to boil this wash water down before adding it to the solution in order to prevent the volume from becoming too great. The extraction of copper is based on the assays and weights of the heads and tails, and not on the analyses of solutions

The column in Table 7 labeled "cc. of water added" gives the amount of water put in the agitator at the beginning of the leach, the purpose of this being to keep the strength of acid that first comes in

contact with the calcine as low as possible. The exact procedure of leaching will probably be more clear if a single leach is described in greater detail. For example, in Leach No 5, 500 cc. of water was first placed in the agitator, along with approximately 200 grams of the calcine About 1000 cc of the solution was now slowly added and also the remaining 200 grams of calcine and 2 grams of MnO_2 The solution was now heated and leaching continued for about one hour, or until most of the acid was neutralized Ten grams of CaO were now added, and leaching continued for four hours At the end of this time the solution was reacidified by the addition of 700 cc more of the original solution, and leaching was continued for four more hours The method used in all of the other leaches was very similar to this, although the time of neutral leaching varied somewhat

Later tests showed that the importance of keeping down the strength of acid in the first part of the leach was not as great as was originally supposed, because the copper dissolved much more rapidly than the iron, with the result that the acid was neutralized before an appreciable amount of iron entered the solution It would therefore not be necessary to add water at the beginning of the leach.

The results of particular interest in Table 7 are that the iron did not increase any more after a concentration of about 5 5 grams per liter was reached, and indeed in some cases actually decreased In those cases where the content decreased, it was noted that the time of neutral leaching was longer, which led to the belief that the solubility of the iron after precipitation was a function of the length of time it remained in the form of the precipitated hydroxide A reference[1] to this has been found in the literature which states that "precipitated iron and aluminum hydroxide are not easily redissolved in weak acid solution after a period of standing"

To test this effect two different leaches were run In one the solution was reacidified immediately after the precipitation of the iron was complete In the other the iron was precipitated and agitation continued for a period of 72 hours before reacidifying In the first case it was found that all of the iron redissolved when the acid

[1] "Purification of Copper Sulphate Solutions" by Tillery and Ralston, Technical paper No. 359, U. S Bureau of Mines; pp 40.

strength was increased to about 3%. No additional iron entered the solution, however.

In the second case the analyses of the solution at the start showed 8.7 grams of iron, 10 1 grams of copper and 123 grams of sulphuric acid per liter. 1000 cc. of this solution was agitated for 2 hours with 400 grams of calcine, after which 40 grams of CaO was added and leaching continued for 72 hours. Five grams of MnO_2 was also added at the start in order to oxidize all the iron to the ferric state. After the first four hours of neutral leaching the solution was tested and found to contain only 0.3 grams of iron per liter so that precipitation was nearly complete. After the 72 hours of neutral leaching the solution was reacidified by the addition of 500 cc more of the original solution. Agitation was then continued for two hours at the end of which time the solution was found to contain 3.3 grams of iron per liter and 2.0% free acid. The acid concentration was now increased by several additions of concentrated sulphuric acid. After each addition the charge was agitated for 2 hours and the solution again analyzed in order to determine how much iron redissolved for each acid strength. The following results were obtained:

Strength of Acid	Amount of Iron Redissolved
2.0%	3.3 g /l.
3.4%	4.4 g./l.
4.5%	5.2 g./l.
5.7%	6.5 g./l

This shows that the amount of iron redissolved is a function of both the length of time it remained precipitated and the strength of the acid. It also shows the possibility of keeping the iron content of the solution at any desired point by varying the time of neutral leaching.

Large Scale Laboratory Leaching Tests:

The results of leaching tests, using from 2500 to 3600 grams of Index concentrate ,are given in Table 8 (see insert) The leaching apparatus shown in Figure 2 was used for these runs. The results in general check very well with those obtained in the smaller scale tests, but due to certain mechanical difficulties and the faulty design of the agitators, it was impossible to exercise the same amount of control, so that there are discrepancies due to evaporation, poor agitation, and

mechanical losses of the solution. These mechanical troubles can be overcome.

The iron content is shown to increase slowly with each leach. This was retarded considerably by the amount of solution discarded each time, which was considerably greater than in the small scale tests

General Considerations:

The results of all leaching tests have shown that under the conditions of leaching employed, it is possible to maintain the concentration of iron in the electrolyte at about 5 grams per liter without great difficulty. This concentration could be decreased somewhat by extending the time of neutral leaching, but it is not believed that this will be either necessary or desirable With this concentration of total iron, the concentration of ferric iron during electrolysis will be about 4 grams per liter or less, with which amount it will be possible to get a current efficiency of deposition of about 85% With a lower concentration of ferric iron the efficiency would be increased but not to a great extent, and the added cost of obtaining the more pure electrolyte would probably more than offset the advantage of increased efficiency Also it has been pointed out by several metallurgists that a certain amount of iron is not only beneficial but necessary for proper depolarization and anode protection

It is also possible that in cases where cheap power is available, it will be desirable to let the concentration of iron increase to as much as 10 grams per liter, in which case the time of neutral leaching could be shortened or done away with altogether The point is that the iron can be controlled at nearly any concentration desired.

The calcium oxide added to the leach served a twofold purpose It not only provided a rapid means of precipitating the ferric iron, but also neutralized much of the excess acid regenerated in electrolysis. Its use for this purpose eliminates the necessity of a by-pass of a part of the solution at the end of each leaching cycle, although a small by-pass may be desirable in order to keep the solutions fresh.

The only purpose of the addition of manganese dioxide to the leach was to oxidize the ferrous iron to the ferric state, so that it could be easily precipitated. Ferrous iron is precipitated slowly and after precipitation the hydrate is immediately redissolved when the

solution is reacidified. However, it will not be necessary to add this manganese dioxide unless desired. The result of not adding it will be that the ferrous iron will remain in the solution and consequently the concentration of total iron will be higher for a given period of neutral leaching.

In these considerations so far it has been assumed that the results of laboratory roasting can be duplicated on a commercial scale. Whether or not this can be done will of course only be proven after a thorough trial. However, it is believed that with a properly constructed multiple-hearth furnace, fed with a uniform clean product containing but little FeS_2, there is no reason why a close temperature control cannot be maintained. Again, the tendency in all metallurgical operations at the present time is toward closer control of variables, so that under the pressure of necessity, it is quite probable that such improvements as are necessary to give close temperature control in roasting operations can be made. Some metallurgists, in commenting upon the relation between laboratory and commercial roasting results, maintain that with the best of care in both, an allowance of from 5% to 10% less extraction on a large scale, has to be made for roasting under conditions such as are contemplated. This would reduce the extraction considerably. However, it should be pointed out that in the roasting tests included in this report, the best possible care in the laboratory was not exercised. Furthermore, the leaching solutions were used over and over again, which was not an ideal condition, so that the results obtained should not be far different from those that could be obtained commercially, especially with the present-day advantages of improved furnaces, agitators, thickeners, and filters, all working continuously and with the minimum of labor and trouble.

A tremendous development has come about in the available machinery for a hydrometallurgical process for producing electrolytic copper direct from present day high grade flotation concentrate. Selective flotation has made it even more possible. Those of us who have experienced these vast improvements in mill and metallurgical machinery, during the past thirty years, realize what further advances are possible.

3. Electrodeposition Tests

The results of electrolysis of the solutions from the leaching tests given in Table 7, are shown in Table 9 (see insert). In this table the current efficiencies and voltages recorded are the averages obtained for the entire run, the voltage being measured as the drop between anode and cathode only. The current efficiency is shown to vary with the concentration of ferric iron in the electrolyte In general, the results agree quite well with the values given by Middleton[8] for the effect of ferric iron on current efficiency, although our values in many cases are somewhat higher. This could be accounted for by taking into consideration any differences in the composition of the electrolyte, rate of deposition of the copper, or other variables.

The results of the electrolysis of the solutions from the large scale laboratory leaching tests are shown in Table 10 (see insert). These results are not as accurate as those of the smaller tests although the two agree quite well

In all of these tests the deposit was smooth and firm so long as the circulation of the electrolyte was maintained and the concentration of the copper therein was not allowed to become so low that it could not be supplied to the cathode as fast as it was being deposited If this happened the deposit became red and pulverulent. For example, in Test No. 8, Table 9, the concentration of copper was reduced to 4 5 grams per liter which was so low that with the rate of circulation used, a deficiency of copper in the vicinity of the cathode resulted, and the deposit was no longer firm. In the larger scale tests, where the rate of circulation was less, the copper could not be firmly deposited below about 12 grams per liter, if the same current density was used The point to which the copper content can be reduced during electrolysis will thus depend upon the rate of circulation and current density employed. Where the solutions are used over and over again this factor is not so important. However, if a by-pass is used, it is desirable to reduce the copper content of the waste solution as low as possible electrolytically before running it over scrap iron to remove the last traces. In a laboratory test, using a solution containing 1 0 grams of iron per liter, which was vigorously stirred, the

[8] See our Progress Report No. 1.

copper content was reduced to 2.4 grams per liter and a firm deposit still maintained. A current efficiency of 78% was obtained during the interval of deposition when the concentration of copper was reduced from 4 grams per liter down to 2.4 grams per liter. The current density was 10 amps. per square foot.

During the deposition tests no corrosion of the lead anodes could be noted, although the time of use was probably not long enough to determine effects of this kind. During electrolysis the anodes became coated with a scale of manganese dioxide, which peeled off readily and formed a small amount of sludge in the bottom of the cell.

The power consumption in pounds of copper deposited per kilowatt hour is almost constant It depends upon the current efficiency and voltage. The latter varies with the temperature and composition of the electrolyte, current density, spacing of the electrodes, and the nature of the anode surface. During a deposition test the voltage would be quite high at first, and would then decrease as the concentration of acid in the electrolyte became higher During the last part of the run it would increase due to the decreasing concentration of the copper

Several tests were run in order to determine the effect of variables on voltage and current efficiency Tables 11 and 12 show the way in which the voltage and current efficiency varies during the progress of depositing the copper from a sulphate solution. These solutions contained 1.2 grams of iron per liter, and the anodes were spaced two inches from the cathodes In Table 11 the solution was vigorously stirred while in Table 12 it was not stirred at all. Both tables show the limit to which the copper could be deposited, under the conditions given, and still maintain a smooth and adherent deposit.

Figures 13, 14, 15, and 16 show the effect of other variables on the voltage drop between anode and cathode. In these tests the distance between the anode and cathode was kept constant at two inches, and the lead anodes were well peroxidized It was found that the latter precaution was necessary because, if new lead anodes were used, the results would be very erratic due to surface changes. The use of well peroxidized lead anodes reduced this effect to a minimum although it did not entirely overcome it.

Table. 11. Electrodeposition of Copper from a Sulphate Solution. Current Density = 32 amps. per sq. ft.

Solution Gms. Cu. Per Liter	Solution % H_2SO_4	Weight of Deposit in Grams	Mean Voltage	Current Efficiency	Energy Efficiency	Lbs. Cu. Deposited Per Kw. Hr.
64.0	4.1	9.1	2.4	95.9	48.7	1.05
52.6	5.8	9.0	2.2	94.9	52.5	1 13
41.4	7.6	9.1	2.1	95.4	55.4	1.19
35.8	8 5	4.5	2.0	94.9	57.8	1.24
30.2	9.3	4 4	1.95	92.6	57.8	1.24
24.8	10 1	4.4	1.9	91.6	58.7	1.26
19.4	10.9	4.3	1.9	91.6	58.7	1.26
14 1	11.7	4 2	1.9	89.5	57.4	1.23
8.7	12.6	4.3	1.95	90.4	56.6	1.21
4.9	13.0	4.0	2.05	84.2	50.0	1.07

Table 12. Electrodeposition of Copper from a Sulphate Solution. Current Density = 12 amps. per sq. ft.

Solution Gms Cu Per Liter	Solution % H_2SO_4	Weight of Deposit in Grams	Mean Voltage	Current Efficiency	Energy Efficiency	Lbs Cu Deposited Per Kw Hr.
56 4	2 3	4 64	2.1	97.7	56.8	1.22
50.6	3 2	4.70	1.9	98.6	63.4	1.35
44.9	4 1	4.64	1.8	97 7	66.2	1.42
39.2	5 0	4 62	1.75	97.4	67.9	1.46
33 4	5.9	4.63	1.7	97.6	70.1	1.50
27 6	6.7	4.60	1.7	96.4	69.0	1.48
21.7	7.6	4 51	1.7	94 8	68.1	1.46
16 6	8 4	4.20	1.9	88.6	56.9	1.22
12.0	9.1	3.70	2.2	78.1	43.4	0.93

Figure 15 shows the desirability of increasing the temperature of electrolysis somewhat in order to decrease the power requirements There will be a maximum temperature of course, governed by other considerations, beyond which it will not pay to go. The increase in temperature would also increase the effect of the ferric iron so that this is one of the factors that would have to be considered.

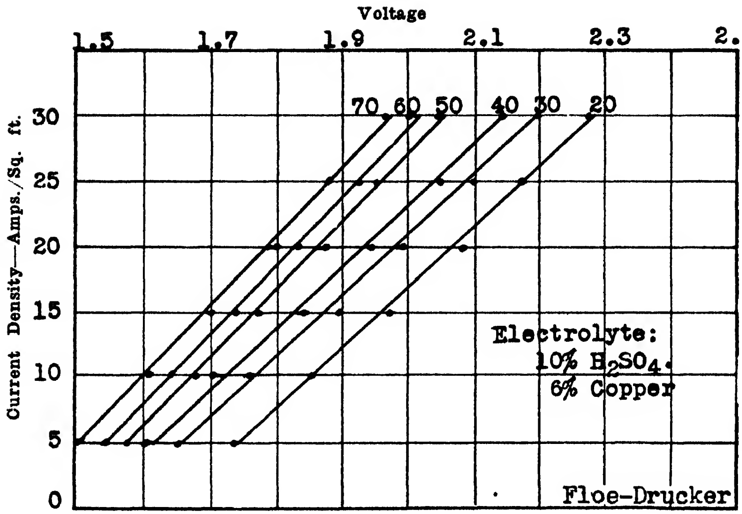

Figure 16 Variation in voltage drop between anode and cathode with the current density. Numbers at top of curves refer to temperature in degrees centigrade.

each test. The preliminary treatment of the residues, prior to cyanidation, varied with the different runs. Some were cyanided directly, some were given an acid wash with 10% H_2SO_4, some a strong alkaline wash, and some an acid wash followed by an alkaline wash In all cases the acid wash was followed by water washes The results show that an acid wash, followed by water washes and then an alkaline wash, will be necessary if the cyanide consumption is to be kept down The reason for this is evident. The original residues coming from the copper leaching plant contain both acid and copper which are cyanicides, and if they are cyanided directly, without preliminary treatment, the consumption of cyanide will be high The high acid leach, followed by the water wash, removes most of the cyanicide copper, and consequently the consumption of cyanide is greatly decreased The final alkaline wash neutralizes the remaining acid, and the consumption of cyanide again decreases considerably.

In the cyanide tests, leached residues containing considerable copper, were purposely used so that the results should show the maximum consumption of cyanide. Leaching the residues with a 10% solution of sulphuric acid, as a preliminary treatment, does not remove all of

Table 13. Analyses of Leached Residues

Sample	% Cu	% Fe.	Gold, oz /T.	Silver, oz./T.
No. 1—From Index Concentrate	2.2	43.5	0.03	5.6
No. 2—From Utah Concentrate	1.0	57.5	0.33	4.2
No. 3—From Utah Concentrate	3.4	54.0	0.30	5.0
No. 4—From Utah Concentrate	4.5	49.1	0.30	4.6

Table 14. Cyanidation of Leached Residues from Utah Concentrate.

Test No	Leach Solution	Cyanide Consumption	% Ext of Gold	% Ext of Silver	Preliminary Treatment
1	0.72% KCN	20.4 lbs/T	91.6	42.9	Washed with solution of NaOH
2	0.72% KCN	10.2 lbs/T	93.3	48.0	Leached with 10% H_2SO_4, followed by NaOH, and water washed.
3	0.72% KCN	9.1 lbs/T	94.1	41.4	Same treatment as in No. 2.
4	0.43% NaCN	45.0 lbs/T	- -	- -	No preliminary treatment.
5	0.43% NaCN	12.2 lbs/T	—	—	Washed with NaOH, followed by water washes
6	0.43% NaCN	11.0 lbs/T	- - -	— -	Leached with 10% H_2SO_4, followed by water washes.
7	0.43% NaCN	6.0 lbs/T	——	--	Leached with 10% H_2SO_4, followed by NaOH, and water washes.
8	0.43% NaCN	3.69 lbs/T	95.1	56.2	Same as No. 7 except more water washes.
9	0.43% NaCN	3.0 lbs/T	96.5	48.1	Same as No. 8 except more water washes.

Note: All samples leached 8 hours except No. 8, which was leached 22 hours

the copper, but apparently it removes nearly all of the cyanicide copper. This is shown by the fact that in Test No. 3 the original residue assayed 3.4% copper, and after being leached with 10% H_2SO_4, it still contained 2 8% copper. Yet, after an alkaline wash, this material was cyanided with a consumption of 9.1 lbs KCN per ton, which, figuring on the basis of equivalent amounts of CN, is equal to 6.8 lbs. NaCN per ton. Again the residues from Test No. 8 and No 9, after cyanidation, assayed 3.7% copper, and yet the cyanide consumption was only 3 and 4 lbs per ton.

The tests that were run show that it is possible to recover the gold and a part of the silver values from the copper leached residues without an excessive consumption of cyanide, if they are given the proper preliminary treatment. Of course, this preliminary treatment and the actual cyanidation will be an added expense, and in the case of many Arizona copper concentrates the values recovered will not be sufficient to make it pay The expense of the strong acid wash should not be great, because it can be accomplished by the agitation of the residues with the by-pass or waste solution from the copper electrodeposition tank house. This method of treament would also recover a part of the copper from the residues, and add to the total extraction of the plant.

In any case the copper leaching plant residues should not be discarded, but should be stacked for some future treatment They are possibly not only valuable for the gold and silver values contained therein, but also as a future source of iron It is doubtful if this iron could be extracted at a profit from such a product under present market and metallurgical conditions, but the high iron content may make it worthy of some future consideration

ECONOMIC CONSIDERATIONS

In order to determine whether a process of this kind is of more than laboratory or academic interest, a careful investigation of the costs involved must be made, and these costs compared with the cost of producing electrolytic copper by present methods. This is a difficult thing to do because the majority of the copper companies do not publish their production costs However ,from an examination of the available

figures the conclusion is drawn that the present day smelting, converting and refining process costs from 2.0 to 4.5 cents per pound of electrolytic copper produced.

The only way of getting at the costs involved in the process outlined in this report is to compare it with other similar hydrometallurgical operations such as the cyanide process for gold and silver, the electrolytic zinc process, and the copper leaching process as it is applied to the treatment of low grade oxidized ores. From such considerations the following estimate is submitted as to the probable cost of recovering electrolytic copper from copper flotation concentrate by the method outlined:

Table 15. Estimated Cost of Treatment of Copper Mill Concentrate Containing 30% Copper. Copper Extracted = 95%

Cost of	Tons Concentrate Treated Per 24 Hours		
	50	500	1000-2000
Roasting	$ 1.50	$0.70	$0.50
Leaching	3.50	2.00	1.50
Electrodeposition	7.50	5.50	4.00
Total cost per ton of concentrate	$12.50	$8.20	$6.00
Total cost per lb of Cu. recovered	2.2 cents	1.4 cents	1.0 cents

N.B. Electric power costs estimated at ⅛ cent to 1 cent per kw. hr.

The estimated cost of this leaching method is from 1 cent to 2.2 cents per pound, as against 2.0 cents to 4.5 cents per pound of electrolytic copper for the smelting method. The gold and silver values are of course not recovered directly by acid leaching so that they must be added to this total cost, or at least the cost of recovering them by cyanidation must be added. However, there are many sulphide copper ores in the United States and elsewhere that contain only negligible quantities of gold and silver, and these should be particularly amenable to this leaching process. Table No. 16 (see insert) shows the average value of the gold and silver in the blister copper produced by several companies. The figures in this table have been calculated from the data of the Mines Handbook for 1931. Tables No. 17 and No. 18 also show figures for the value of gold and silver recovered from American copper ores

Table 17. Copper Ore Produced and Average Extraction Value of Gold and Silver per Ton of Ore in 1929, by States.* (Smelting Process)

State	Short Tons	Average value extracted	Lbs. Copper produced**	Au. & Ag. value (cents) recovered per lb. Cu.
Arizona	25,669,975	$0.28	829,206,475	0.24 cts.
Utah	17,895,332	0.21	325,965,289	1.15
Nevada	6,572,404	0.23	138,990,247	1.09
New Mexico	4,114,187	0.12	100,165,206	0.43
Montana	3,802,976	1.19	299,894,853	1.50
California	1,080,355	0.65	33,084,232	2.12
Tennessee	825,300	0.07	———	Very small amount
Alaska	590,400	0.32	39,867,940	0.47

* U. S. Bureau of Mines Bulletin, 1931, "Gold and Silver in 1929." Page 891.
** Mines Handbook 1931

Table 18. Copper Ore Produced in the U. S. A., and Average Extraction Value of Gold and Silver per Ton, 1920-1929.* (Smelting Process)

Year	Short Tons	Au. & Ag. value extracted per ton	Total lbs Cu. produced**	Au & Ag value (cents) per lb. copper
1906		$1.55	917,805,682	
1920	32,447,410	0.52	1,209,061,043	1.3
1921	10,930,888	0.54	505,586,098	1.1
1922	23,356,128	0.56	950,285,947	1.3
1923	41,596,309	0.42	1,434,999,962	1.2
1924	44,887,379	0.39	1,634,249,192	1.0
1925	47,186,114	0.42	1,674,869,886	1.1
1926	51,064,058	0.36	1,739,622,094	1.0
1927	49,966,438	0.32	1,684,040,983	0.95
1928	55,870,147	0.31	1,825,900,393	0.95
1929	62,140,833	0.31	2,002,863,135	0.96

* U. S Bureau of Mines Bulletin, 1931 "Gold and Silver in 1929" Page 893
** Mines Handbook 1931

It is interesting to note in Table No 18 that these values are decreasing every year

The cost of producing electrolytic zinc by electro-hydrometallurgical methods varies from 1 9 cents to 2 1 cents per pound

The cost figures as given here are believed to be accurate insofar as it is possible to gather them from the available published data However, it is realized that there are conditions and limits to the extent of their application Any additional cost figures or corrections would be welcome. Discussion of the economic phase of this problem is cordially invited

CONCLUSIONS

From the results obtained, the following conclusions are drawn·

1. By a careful control of the roasting temperatures, a calcine can be produced in which over 95% of the copper is in a form that is soluble in a 4% solution of sulphuric acid At the same time all but 2% to 5% of the total iron can be made insoluble The temperature control necessary is no greater than can be attained by the careful operation of present-day multiple hearth furnaces of the type used in smelters

2 There is little advantage in using a solvent stronger than 3% or 4% H_2SO_4 With higher strengths of acid the copper extraction is increased a small amount, but the advantage gained is more than offset by the disadvantage of the increased amount of iron that is dissolved

3 The amount of iron in the electrolyte increases very slowly, even if no attempt is made to purify the solution, provided that the roast has been properly conducted The solubility of the iron is much less in old solutions than in fresh ones.

4. The amount of iron in the electrolyte can be readily controlled It is easily precipitated from the neutral solution by calcium oxide, and the precipitated hydrate is not all redissolved in the strength of acid necessary to extract the copper.

5. The solubility of the ferric hydrate after precipitation is a function of the strength of the acid solution and the length of time it remained precipitated. It is also probably a function of the amount of iron already contained in the leach solution

6. No attempt should be made to keep the iron content below four or five grams per liter. This can be readily done, and at this concentration it is beneficial rather than detrimental.

7. The excess acid regenerated during electrolysis, due to the presence of sulphate in the roast, can easily be neutralizd by milk of lime. At the same time the latter can be used as a hydrolytic agent for the precipitation of iron from the solution. This does away with the necessity of a by-pass, although a small amount may be desirable in order to keep the solutions in good condition.

8. The use of MnO_2 as an oxidizing agent is not necessary, unless it is desired to precipitate all of the iron from solution. Approximately 75% of the iron in the solution after electrolysis is in the ferric form and can be precipitated without the use of any MnO_2.

9. Electrolysis of the solutions containing as high as five grams of iron per liter does not present any difficulty. A high grade and firm deposit can be produced with a power consumption of less than 1 kw hr. per pound of copper.

10. If a by-pass is used, the copper remaining in the solution after electrolysis can be readily precipitated as cement copper on sponge iron. The cement copper can be roasted to the oxide form and turned back into the leaching tanks, so that the only product of the plant is practically pure electrolytic copper. The sponge iron can be cheaply manufactured from the copper leaching plant residues as they contain a high percentage of iron.

11. Where the gold and silver values in the copper leached residues are sufficiently high, they can be cyanided with a consumption of less than five pounds of NaCN per ton. In order to do this the residues must first be given an acid wash with 10% H_2SO_4 solution, followed by water washes, and then an alkaline wash. If the washing is sufficient, practically all of the cyanicides will be removed by this method of treatment. There may still be considerable copper present, but it will not act as a cyanicide.

The results show that it is possible to produce high grade electrolytic copper on a laboratory scale by the method outlined. Experience has shown that laboratory results can be closely duplicated on a commercial scale, if the same conditions as far as possible are observed. This is sometimes difficult to do, but the problem can be solved by improvements in equipment or, if necessary, the invention of new

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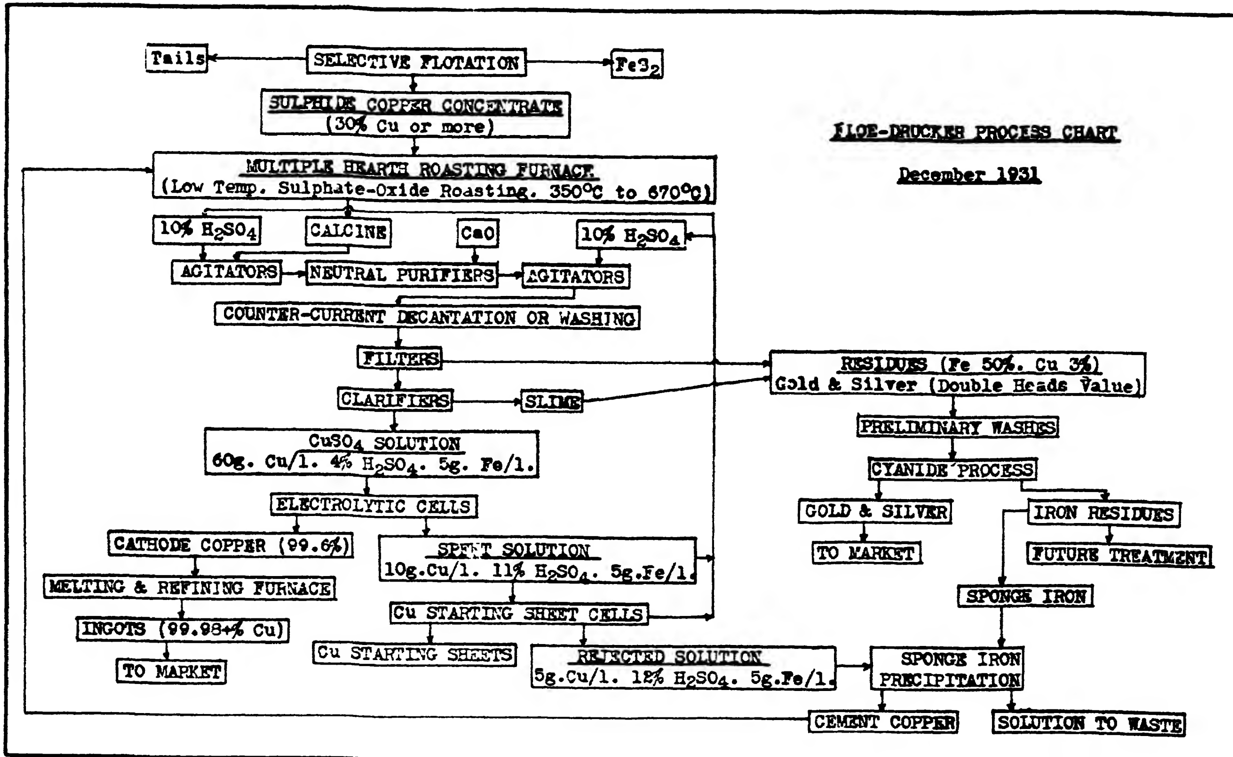
December 1931



machines. Hydrometallurgical equipment has already been developed to a high degree, due to the introduction of the cyanide process for gold and silver, and to the electrolytic zinc process, so that the application of this method of treatment to the recovery of copper from mill concentrate is greatly simplified

The economics of the process should be given very careful consideration Selective flotation, the key to this problem, has advanced to such an extent that a high grade copper concentrate is now available for treatment These finely divided concentrates are well adapted to treatment by this leaching process.

In a good many cases a considerable saving is possible, in other cases it will be necessary, of course, to debit the cost of precious metal recovery against the economies made in copper recovery by this newly applied method for concentrate In many cases this may prove a deciding factor It is a very practical subject for research, and it would appear that the battle for lower cost of production for American copper must be fought all over again

Let it be understood, however, that the tests as given in this report are of a laboratory nature, and that the next stage in the development of our process should be the erection of a continuously operating pilot-plant to check these results on a commercial scale Lack of funds makes it impossible for us to carry on experiments of this size in our laboratories However, it is hoped that enough interest will be created in this process so as to make sufficient funds available for our continuation with this work

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MONTHLY BULLETIN

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The Relative Lubricating Values of Automotive Oils

by

Howard H. Langdon

ENGINEERING BULLETIN No. 41

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

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The Relative Lubricating Values of Automotive Oils

by

Howard H. Langdon*

INTRODUCTION

Many users of automotive equipment have written to the State College of Washington wishing to know what features are important in considering the choice of a lubricant.

It is the purpose of this study to answer these questions as fully as possible by reporting the results of a series of tests made in the laboratory and of other tests made on equipment in normal operation in the field. A large amount of data has been obtained that will be of interest to the practical user, and, in addition, data that are important to those concerned with the technical phases of automotive lubrication Inasmuch as this report is of a practical nature, intended to enlighten the non-technical user, only those experimentally determined facts that are of vital interest to the ultimate user will be given. No statements are made unless there is experimental evidence to substantiate them, except of course where the opinions of other investigators are quoted. Technical terms which may be confusing will be avoided whenever possible.

Technical details of this study are published in Bulletin No. 42.

CHOOSING A LUBRICANT

The buyer of a lubricant for automotive engines is confronted with the necessity of choosing between four general types of mineral lubricating oil as well as between several different grades of each type. These four types are:

A. Asphalt or "Napthene" base, commonly known as western

B. Mid-Continent

* The writer is indebted to Homer J. Dana, and Dr. R. W. Gelbach of the State College of Washington and O. W. Collins, Byron Baldwin, and E. E. King, farmers in the vicinity of Pullman, for their fine cooperation in obtaining the data on which this study is based

C. Paraffin base, commonly known as eastern

D. Blended oil

The range in price of the above oils as retailed in the State of Washington is as high as 2½ to 1. The thoughtful user then wants to know if the lubricating value of these oils bears any relation to their first cost. On the basis that the public has the right to know the truth regarding the lubricating value of the various types of oils available, the results of the following tests are submitted for what they may be worth.

SCOPE OF THE STUDY OF LUBRICATING OILS

Six different series of tests were conducted over a period from 1925 to 1932, and included approximately 9400 miles of automobile operation and more than 800 hours of laboratory, harvester, and tractor operation. No attempt has been made to study a large number of brands of oil, but rather to study the relative value of the two distinct types: that is, paraffin and asphalt base oils. With the exception of one oil noted later, oils of types B and D were not tested in this study.

SIX SERIES OF TESTS MADE

1. In the first series, a four-cylinder truck engine was operated for a total of 68 hours in the laboratory. Asphalt and paraffin base oils were alternated in the four runs of this test.

2. During the summer of 1926, two Model 1925 Oakland cars which had traveled approximately the same mileage were driven a total of 6400 miles under controlled conditions. Oil tests were made in the engines of these cars which were being used in the determination of relative tire wear on various types of highway surfaces.[1]

3. Tests were conducted during the summer of 1929, on a car used on the highways for studying "Rhythmic corrugations in highways."[2] Six tests of 500 miles each afforded a study of two brands of oil representing the paraffin and the napthene bases.

4. The fourth series of tests included thirteen separate runs of 12 hours each on an automobile engine mounted in the laboratory. All

[1] Engineering Bulletin No. 18 Eng. Exp. Sta. State College of Washington.

[2] Engineering Bulletin No. 31 Eng. Exp. Sta. State College of Washington.

conditions of operation were under complete control, thus affording some very reliable data.

5. A study was made during the summer of 1931, including 100 hours of operation in the field, of a Case combined harvester engine, in which two brands were tested, representing the two types of oil.

6. Tests were made on two Caterpillar tractors, operated on farms during the plowing and planting season of 1932. Approximately 520 hours of tractor operation afforded a study of five brands representing three types of oil.

METHOD OF CONDUCTING TESTS

An attempt was made during the first tests to determine the relative merits of different types of oil by measuring the amount of wear. This was done by weighing piston rings and noting the change of dimensions of the wearing parts of an engine. Experience soon showed that this method of testing was subject to errors so large as to make the results unreliable Subsequent tests, therefore, were based on the analysis of samples of the oil in the crank-case to determine its iron content.

Commencing with the second series, and continued with but minor variations throughout all of the subsequent tests, the method was as follows:

A paraffin oil was carefully measured and placed in engine number 1 A like quantity of asphalt base oil was placed in engine number 2. Petcocks had been installed in the pipe line from the oil pump to the bearings for taking samples at stated intervals. Both cars were operated together over the same highways at a fixed speed. At the end of 200 miles, and while the engine was thoroughly heated, and still running, four-ounce samples of oil were drained from each engine into separate prescription bottles. This was repeated at 400, 600, and 800 miles. By taking the sample only when the engine was thoroughly heated, and before stopping, it was assured that the sample was representative of all the oil in the crank-case at the time of withdrawal.[3] At 400 miles, and at the end of the run at 800 miles, the quantity of

[3] The fact that the iron content of the samples withdrawn was representative of the wear taking place has been proven in subsequent tests.

oil remaining in the crank-case was determined by draining and weighing. This made it possible to determine the relative oil consumption during the progress of the test. At the end of the test, both engines were drained and the crank-cases were flushed for five minutes with a special flushing oil. This was drained, and new oil carefully weighed in. On each consecutive 800-mile test, the method was the same, except that the two types of oil were reversed between cars to eliminate the question of unequal wear caused by mechanical condition of the engines

Much the same procedure was followed in series three, except that a single 1926 Chevrolet coach was used. Samples were drawn every 100 miles, and a change of oil was made every 500 miles Six runs were made, using two additional brands of oil, representing the two types

In series four, a four-cylinder engine from the car used in the preceding tests was reconditioned for use in the laboratory. It was mounted to drive an alternating current induction motor as a generator[4] which was electrically connected to the college power system.

This assured a closely constant speed, and at the same time made use of the electricity generated during the test. All the necessary meters and instruments were installed so that consecutive runs could be duplicated, and any variation in performance of the engine could be determined. Readings were made of fuel consumption and of electrical output to determine if there were any differences in the engine output depending upon the various oils used. Crank-case vapors were condensed and tested, and temperatures of oil, and cooling water taken from which the "heat balance" could be computed. At the end of each of the first five runs, the engine was dismantled, the piston rings were weighed, and the carbon was scraped from the piston head and upper cylinder walls. The weights of the piston rings before and after a run showed quite definite wear, but previous experiments had shown the results to be unreliable. Careful study of the tests in this series showed that in spite of extreme care in trying to replace the rings exactly as they had been, there seemed to be a necessary period of rapid wear before the rings would settle down to steady operation, thus making

[4] **Furnished by Century Electric Co., Spokane, Washington.**

it impossible to obtain satisfactory results in this way. In the following eight runs, the pistons were not removed from the cylinders, but the crank-case was opened after each run and thoroughly cleaned.

Types of oil were alternated during consecutive runs Four brands, representing the two types, were used Oil samples were drawn from the high pressure oil line every two hours, and measurements of the quantity of oil remaining in the crank-case were made every hour. Each run was twelve hours long, with no stop and no variation in load. The data taken during this series have shown the accuracy of the oil analysis method of making these tests.

In the tests made on the Case combined harvester engine, oil samples were drawn off at noon, and again at night Each sampling was preceded by five hours of operation, the sample being drawn before the engine was allowed to stop Two brands of oil, representing the two types, were alternated during the consecutive runs. At stated intervals determination was made of the quantity of oil remaining in the crank-case. Four runs of twenty-five hours duration each, were made during the 1931 harvest season.

During the following spring and summer, similar tests in all respects were made on two Caterpillar "30" tractors, which were being used for plowing and seeding Eleven runs were made, of from 40 to 60 hours duration each, using five brands of oil representing Pennsylvania paraffin, a mid-continent paraffin, and a western or asphalt base.

THE OILS USED

For obvious reasons, the different brands of oil used cannot be named in this report. However, they are numbered and described by their physical properties, so that the two types can be readily identified. Whenever possible, the oil was purchased on the open market in sealed containers. In other cases, the writer purchased direct from the service station operator, making sure, insofar as possible, that the oil obtained was what it was represented to be. No attempt has been made to adapt an oil to the engine. For instance, if a manufacturer or a lubricating chart indicated that a "heavy" bodied oil should be used during the summer months two oils, of "heavy" grade, representing the two types, were purchased, regardless of the relative viscosities of the two oils. In some instances it was found that so far

as the operating temperature was concerned, and the viscosity at this temperature, a heavy body oil of one type and a medium body oil of another type would have more nearly the same viscosities at the operating temperature. This procedure is not justified from a strictly laboratory standpoint, but is justified on the basis that this study is for the benefit of the ultimate user of the oil.

Table 1 shows the oils used, the type, the series of tests in which used, the date purchased, the body rating, and also the physical properties. Throughout the tests, the paraffin and the asphalt base oils were alternated so that direct comparisons could be made between the two types. Among the oils listed in Table 1 are eight brands, as sold by the various oil companies. Direct comparison is made between oils 3 and 4, 9 and 11, 12 and 13, 17 and 18, 19 and 21, which are paraffin base and asphalt base respectively. Oils 3 and 17 are oils of the same brand that were purchased six years apart and tested under different circumstances. Although oil 3 was purchased as "heavy" and oil 17 as S.A E. 40, their viscosities are quite different. In the meantime this company brought out oil No 9 with a new name and advertised it as an oil superior to their previous oil no. 3; however, no marked superiority could be found in the physical property tests or wear tests. The same company also furnished their customers with a paraffin base oil, nos 4, 11, and 18, over the same period of time. At the present time oil no 9 is sold by this company as a high grade asphalt base oil and is their main "stock in trade." Oil no. 18 is furnished to those demanding a paraffin base oil while oil no. 17 is sold as an inferior asphalt base lubricating oil at a very low cost to the consumer to meet competition in price.

This same arrangement exists in other companies; for instance, oils 12 and 15 are the main "stock in trade" representing asphalt base oils of different "body." Oils 13 and 21 are sold to those demanding a paraffin base oil while oil no 19 is the inferior asphalt base lubricating oil, not recommended, but sold to meet competition. Oils nos. 14 and 20 were of one brand and classified as a mid-continent paraffin.

DETAILS OF ANALYSIS OF CRANK-CASE OILS

The underlying principle governing all of the tests has been to compare the two general types of oil, either by running the two oils

Table 1. Physical Properties of Oils Used in Tests

Oil No	Type	Body Rating	Series of Tests Used	Date Purchased	Specific Gravity at 60/60°F.	Flash Point °F.	Fire Point °F.	Pour Point °F.	Carbon Residue %	Viscosity Saybolt Second 100°F.	130°F.	210°F.
1	Paraffin	Medium	1	June '25	876	450	505		.75	321	158	57
2	Asphalt	Medium	1	June '25	.927	340	370			400	163	52
3	Asphalt	Heavy	2	June '26	.939	360	405		.29	655	230	60
4	Paraffin	Heavy	2	June '26	.883	427	470		.805	410	200	60
5	Asphalt	Heavy	2	July '26	.982	375	420	0	207	470	195	55
6	Paraffin	Heavy	2	July '26	.879	450	505		.366	334	165	57
7	Asphalt	Heavy	3	June '29	.938	365	425	5	.07	553	215	56
8	Paraffin	Heavy	3	June '29	882	460	510	40	.90	756	357	83
9	Asphalt	S A E 40	4	March '31	.939	400	450	15	.375	1244	400	83
10	Paraffin	S A E 40	4	March '31	.884	450	505	15	.88	627	302	82
11	Paraffin	S A E 40	4	April '32	8844	440	485	25	.80	615	260	70
12	Asphalt	S A E 30	4	August '32	.9303	400	445	5	.19	702	264	61
13	Paraffin	S A E 30	4	August '32	.8811	435	490	15	.56	431	204	63
14	Paraffin*	S A E 30	4	August '32	.905	425	480	0	.35	645	264	69
15	Asphalt	S A E 40	5	August '31	9328	415	470	5	.34	1009	340	68
16	Paraffin	S A E 40	5	August '31	.887	475	520	0	.85	649	285	74
17	Asphalt	S A E 40	6	May '32	.923	405	475	10	.55	1505	565	88
18	Paraffin	S A E 40	6	May '32	.8844	425	485	15	.85	685	270	66
19	Asphalt	S A E 40	6	June '32	9273	395	440	5	.30	820	300	65
20	Paraffin*	S A E 40	6	June '32	.9036	445	495	5	.95	950	360	78
21	Paraffin	S A E 40	6	June '32	.8816	445	505	15	.80	670	270	66

in two separate engines where available, as in series two, or by alternating the oils on consecutive runs in the same engine. The same principle was carried out in analyzing the used oils. As a rule, five samples of one type of oil were always analyzed with five similar samples of the other type. This prevented any favor to one oil over another.

SUMMARY OF RESULTS OBTAINED

The relative wear occurring between the two types of oil, paraffin and asphalt base, for all of the series, is shown in Table 2.

Table 2

Series Number	Averages of total wear in grams—asphalt base	Averages of total wear in grams—paraffin base	Ratio of wear asphalt to paraffin
2—(4 runs per car, 800 miles per run with 2 cars)	845	.47	1.80—1
3—(6 runs, 500 miles per run, 1 car)	99	.63	1.57—1
4—(7 runs, 12 hours each, laboratory)	75	.395	1.90—1
5—(4 runs, 20 hours each, harvester engine)	8.4	6 7	1.25—1
6—(11 runs, 40 to 60 hours, 2 Caterpillar tractors)	28 0	24.1	1.16—1
Weighted average of all tests*			1.49—1
Weighted average of auto and lab. tests			1.76—1
Weighted average of farm tests			1.18—1

* In determining the weighted average wear for all tests, the individual engines, which were different in size and construction details, were rated in terms of relative total piston surface traversed in a given period of time. It has been determined in these tests that approximately 80% of the iron appearing in the samples was worn from the cylinder walls, piston rings and from the piston surfaces. The relative rate of wear occurring in the laboratory and in the field was determined upon this basis of engine rating. The results should show without question the serious effect of dust and foreign material in field operation.

From Table 2 it will be seen that the harvester and tractor engines show a far greater rate of wear than the automobile and laboratory engines. The engines used in these tests were not of the same rating, speed or number of cylinders. An approximate factor has been

arrived at for each engine, which, when applied to the individual engines will correct for these differences. Correcting for both the length of run and the difference in engine characteristics, wear proceeded in the harvester engine, 7 times more rapidly than it would have occurred under laboratory conditions. Likewise in the tractor engine wear proceeded at 18 times the laboratory rate This increased rate of wear can be explained by the severe dirt and dust conditions under which the tractors operate when compared to operation under laboratory conditions.* Additional proof that abrasive dust particles are responsible for the rapid wear can be found in three observed facts. 1st. Wear increased with the dryness of the season. In the first part of the season when the ground was still damp from the spring rains, a relatively small wear occurred in the individual runs. 2nd. In the oil analysis procedure, it was observed that high iron content in the individual samples was coincident with high alumina and silica content (dust).[8] 3rd. Tractors used on Palouse wheat farms often require a rebore and refitting of pistons and rings each year

Table 3

Test Series	No Runs Each Oil	Approx Hrs. Each Run	Average Per Cent Oil Consumption Asphaltic	Paraffin
2	4	26	48	40
3	3	22	45	26
4	6	12	45	34
5	2	25	11	13
6	5	50	30	37
Weighted average of all tests			38	33

[8] Observations and calculations have been made to determine what portion of the iron in the sample was due to ferrogenous earth, and was determined to be a negligible percentage.

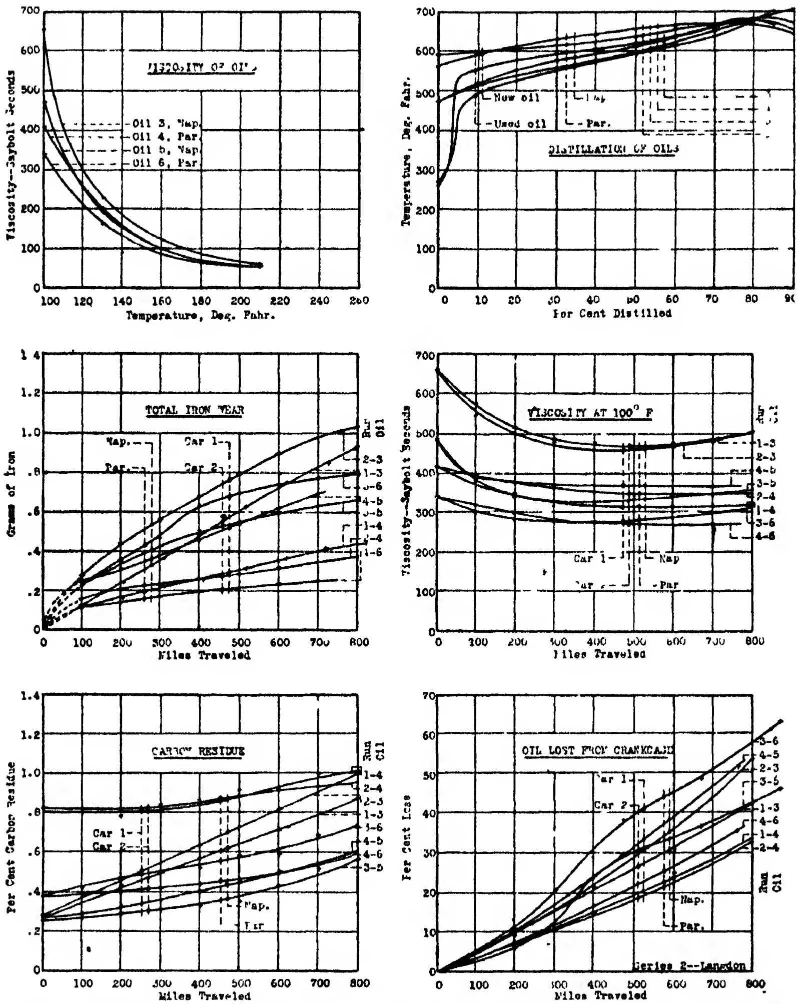

Figure 1. Two Oakland coaches traveling 30 MPH on relatively clean highways.

Note that abbreviation ''Par'' represents oils having a paraffin base, while 'Nap'' represents oils having an asphalt, or napthene base.

CONCLUSIONS

It should be remembered that the foregoing study is in the field of automotive lubrication only, and that it covers what are considered to be a few typical oils representing the asphalt and paraffin bases. The oils chosen are those that are in direct competition throughout most of the United States and are representative of many other oils sold.

This series of tests, while not as extensive as other tests upon the change in physical properties of lubricating oil during use, has gone deeper into the heart of the problem than any reports so far published have indicated. Wear of important parts of the automotive engine determines the maintenance cost which is, as a rule, greater than the difference in cost between high and low grade lubricating oils

As a result of this study the following conclusions can be drawn:

1. To the consumer the so-called physical property tests of lubricating oils are of value chiefly for the purpose of identification, and for making certain that the oils purchased are up to the manufacturer's specifications.

2. Viscosity tests are of value in adapting a lubricating oil to the needs of an engine, and for the identification of oils, but do not necessarily indicate the lubricating value of an oil. A paraffin base oil, as a rule, maintains a more uniform viscosity with use than does an asphalt base oil.

3. Distillation tests and flash and fire tests are useful for identification and refinery control, but it is doubtful if there is any direct relation between these tests and lubricating value. Cloud and pour tests may be important for selecting oils to be used in extremely cold weather, but are not a guide in determining lubricating value for normal operation.

4. An oil testing high in carbon residue does not necessarily possess inferior lubricating properties. The foregoing tests indicate that oils with high initial carbon residue have shown superior lubricating ability, although this study would seem to indicate that there is no direct relation between the two. The carbon residue test should be used only as a means of refinery control and identification. Where

other investigators have shown that the carbon residue values influence the rate of carbon deposition in the combustion chamber, the foregoing tests would seem to indicate that other influences, such as leakage past the rings, were much more important in forming carbon deposits.

5. Operation under dusty conditions, such as farm work, reveals the desirability of dust-proofing such engines. In these tests excess wear due to dust reached as high as 2000%, and consequently the comparative value of any lubricant was accordingly diminished. However, even in this case somewhat less wear was shown for the paraffin base oil.

6. In the comparative tests, leakage and pumping losses were greater by as much as 6% with the asphalt than with the paraffin base oils.

7. In automobile, laboratory, and field operation of the automotive engines used in these tests, an average of 54% greater wear of the working parts took place with typical asphalt base oils than with typical paraffin base oils.

Partial List, Bulletins
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21. Magnetic Nail Picker for Highways.
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Laboratory Methods of Comparing Lubricating Values of Automotive Oils

by

Howard H. Langdon

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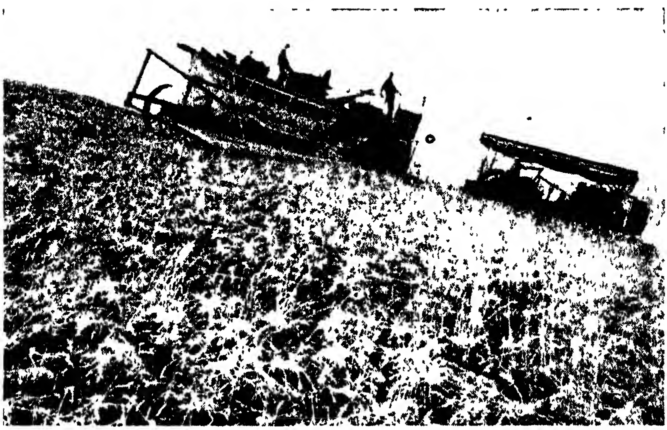

Great care should be used to provide clean air for the engines on expensive harvesting machinery. Next in importance is the choice of a suitable lubricant, and its renewal at frequent intervals

Laboratory Methods of Comparing Lubricating Values of Automotive Oils

by

Howard H. Langdon*

INTRODUCTION

The rapid increase in recent years in the use of automotive equipment of all kinds has opened up an attractive field to various oil companies for the sale of lubricants As a result of keen competition among advertisers of these products, users are frequently confused or misled as to the relative lubricating value per dollar cost of the various oils offered for sale Many such users have written to the State College of Washington seeking information as to the relative lubricating value of different kinds of oil, and especially of the so-called eastern and western oils. Inasmuch as there is frequently considerable difference in the first cost of different lubricants even of the same general class, the question becomes one of considerable economic importance to the user Too often he is induced to judge the value of an oil by its price alone, when, in fact, that may easily be the least important feature of that oil.

It is the purpose of this study to answer these questions as fully as possible by reporting the results of a series of tests made in the laboratory and of other tests made on equipment in normal operation in the field A large amount of data has been obtained that will be of interest to the practical user, and, in addition, data that are important to those concerned with the technical phases of automotive lubrication Inasmuch as this report is of a practical nature, intended to enlighten the non-technical user, only those experimentally determined facts that are of vital interest to the ultimate user will be given. No statements are made unless there is experimental evidence to substantiate

* The writer is indebted to Homer J Dana, and Dr R W Gelbach of the State College of Washington and O W. Collins, Byron Baldwin, and E E King, farmers in the vicinity of Pullman, for their fine cooperation in obtaining the data on which this study is based

them, except of course where the opinions of other investigators are quoted. Technical terms which may be confusing will be avoided whenever possible

CHOOSING A LUBRICANT

The buyer of a lubricant for automotive engines is confronted with the necessity of choosing between four general types of mineral lubricating oil as well as between several different grades of each type. These four types are:

A Asphalt or "Napthene" base, commonly known as western

B. Mid-Continent

C. Paraffin base, commonly known as eastern

D Blended oil

The range in price of the above oils as retailed in the State of Washington is as high as 2½ to 1 The thoughtful user then wants to know if the lubricating value of these oils bears any relation to their first cost. On the basis that the public has the right to know the truth regarding the lubricating value of the various types of oils available, the results of the following tests are submitted for what they may be worth.

SCOPE OF THE STUDY OF LUBRICATING OILS

Six different series of tests were conducted over a period from 1925 to 1932, and included approximately 9400 miles of automobile operation and more than 800 hours of laboratory, harvester, and tractor operation No attempt has been made to study a large number of brands of oil, but rather to study the relative value of the two distinct types: that is, paraffin and asphalt base oils With the exception of one oil noted later, oils of types B and D were not tested in this study

SIX SERIES OF TESTS MADE

1 In the first series, a four-cylinder truck engine was operated for a total of 68 hours in the laboratory Asphalt and paraffin base oils were alternated in the four runs of this test.

2. During the summer of 1926, two Model 1925 Oakland cars which had traveled approximately the same mileage were driven a

total of 6400 miles under controlled conditions. Oil tests were made in the engines of these cars which were being used in the determination of relative tire wear on various types of highway surfaces.[1]

3. Tests were conducted during the summer of 1929, on a car used on the highways for studying "Rhythmic corrugations in highways."[2] Six tests of 500 miles each afforded a study of two brands of oil representing the paraffin and the napthene bases.

4. The fourth series of tests included thirteen separate runs of 12 hours each on an automobile engine mounted in the laboratory All conditions of operation were under complete control, thus affording some very reliable data.

5. A study was made during the summer of 1931, including 100 hours of operation in the field, of a Case combined harvester engine, in which two brands were tested, representing the two types of oil.

6 Tests were made on two Caterpillar tractors, operated on farms during the plowing and planting season of 1932 Approximately 520 hours of tractor operation afforded a study of five brands representing three types of oil

METHOD OF CONDUCTING TESTS

An attempt was made during the first tests to determine the relative merits of different types of oil by measuring the amount of wear. This was done by weighing piston rings and noting the change of dimensions of the wearing parts of an engine Experience soon showed that this method of testing was subject to errors so large as to make the results unreliable Subsequent tests, therefore, were based on the analysis of samples of the oil in the crank-case to determine its iron content

Commencing with the second series, and continued with but minor variations throughout all of the subsequent tests, the method was as follows:

A paraffin oil was carefully measured and placed in engine number 1. A like quantity of asphalt base oil was placed in engine number 2 Petcocks had been installed in the pipe line from the oil pump to the

[1] Engineering Bulletin No 18 Eng Exp. Sta State College of Washington
[2] Engineering Bulletin No. 31 Eng Exp. Sta. State College of Washington

bearings for taking samples at stated intervals Both cars were operated together over the same highways at a fixed speed At the end of 200 miles, and while the engine was thoroughly heated, and still running, four-ounce samples of oil were drained from each engine into separate prescription bottles This was repeated at 400, 600, and 800 miles By taking the sample only when the engine was thoroughly heated, and before stopping, it was assured that the sample was representative of all the oil in the crank-case at the time of withdrawal [3] At 400 miles, and at the end of the run at 800 miles, the quantity of oil remaining in the crank-case was determined by draining and weighing This made it possible to determine the relative oil consumption during the progress of the test At the end of the test, both engines were drained and the crank-cases were flushed for five minutes with a special flushing oil This was drained, and new oil carefully weighed in. On each consecutive 800-mile test, the method was the same, except that the two types of oil were reversed between cars to eliminate the question of unequal wear caused by mechanical condition of the engines

Much the same procedure was followed in series three, except that a single 1926 Chevrolet coach was used Samples were drawn every 100 miles, and a change of oil was made every 500 miles Six runs were made, using two additional brands of oil, representing the two types.

In series four, a four-cylinder engine from the car used in the preceding tests was reconditioned for use in the laboratory It was mounted to drive an alternating current induction motor as a generator[4] which was electrically connected to the college power system

This assured a closely constant speed, and at the same time made use of the electricity generated during the test All the necessary meters and instruments were installed so that consecutive runs could be duplicated, and any variation in performance of the engine could be determined. Readings were made of fuel consumption and of electrical output to determine if there were any differences in the engine output depending upon the various oils used Crank-case vapors were

[3] The fact that the iron content of the samples withdrawn was representative of the wear taking place has been proven in subsequent tests

[4] Furnished by Century Electric Co , Spokane, Washington.

condensed and tested, and temperatures of oil, and cooling water taken from which the "heat balance" could be computed. At the end of each of the first five runs, the engine was dismantled, the piston rings were weighed, and the carbon was scraped from the piston head and upper cylinder walls. The weights of the piston rings before and after a run showed quite definite wear, but previous experiments had shown the results to be unreliable. Careful study of the tests in this series showed that in spite of extreme care in trying to replace the rings exactly as they had been, there seemed to be a necessary period of rapid wear before the rings would settle down to steady operation, thus making it impossible to obtain satisfactory results in this way. In the following eight runs, the pistons were not removed from the cylinders, but the crank-case was opened after each run and thoroughly cleaned

Types of oil were alternated during consecutive runs. Four brands, representing the two types, were used. Oil samples were drawn from the high pressure oil line every two hours, and measurements of the quantity of oil remaining in the crank-case were made every hour Each run was twelve hours long, with no stop and no variation in load. The data taken during this series have shown the accuracy of the oil analysis method of making these tests.

In the tests made on the Case combined harvester engine, oil samples were drawn off at noon, and again at night. Each sampling was preceded by five hours of operation, the sample being drawn before the engine was allowed to stop. Two brands of oil, representing the two types, were alternated during the consecutive runs. At stated intervals determination was made of the quantity of oil remaining in the crank-case Four runs of twenty-five hours duration each, were made during the 1931 harvest season.

During the following spring and summer, similar tests in all respects were made on two Caterpillar "30" tractors, which were being used for plowing and seeding Eleven runs were made, of from 40 to 60 hours duration each, using five brands of oil representing Pennsylvania paraffin, a mid-continent paraffin, and a western or asphalt base.

THE OILS USED

For obvious reasons, the different brands of oil used cannot be named in this report. However, they are numbered and described by

their physical properties, so that the two types can be readily identified. Whenever possible, the oil was purchased on the open market in sealed containers. In other cases, the writer purchased direct from the service station operator, making sure, insofar as possible, that the oil obtained was what it was represented to be. No attempt has been made to adapt an oil to the engine. For instance, if a manufacturer or a lubricating chart indicated that a "heavy" bodied oil should be used during the summer months two oils, of "heavy" grade, representing the two types, were purchased, regardless of the relative viscosities of the two oils In some instances it was found that so far as the operating temperature was concerned, and the viscosity at this temperature, a heavy body oil of one type and a medium body oil of another type would have more nearly the same viscosities at the operating temperature This procedure is not justified from a strictly laboratory standpoint, but is justified on the basis that this study is for the benefit of the ultimate user of the oil.

Table 1 shows the oils used, the type, the series of tests in which used, the date purchased, the body rating, and also the physical properties. Throughout the tests, the paraffin and the asphalt base oils were alternated so that direct comparisons could be made between the two types Among the oils listed in Table 1 are eight brands, as sold by the various oil companies Direct comparison is made between oils 3 and 4, 9 and 11, 12 and 13, 17 and 18, 19 and 21, which are paraffin base and asphalt base respectively Oils 3 and 17 are oils of the same brand that were purchased six years apart and tested under different circumstances Although oil 3 was purchased as "heavy" and oil 17 as S.A E 40, their viscosities are quite different. In the meantime this company brought out oil No 9 with a new name and advertised it as an oil superior to their previous oil no 3, however, no marked superiority could be found in the physical property tests or wear tests The same company also furnished their customers with a paraffin base oil, nos 4, 11, and 18, over the same period of time At the present time oil no 9 is sold by this company as a high grade asphalt base oil and is their main "stock in trade" Oil no 18 is furnished to those demanding a paraffin base oil while oil no 17 is sold as an inferior asphalt base lubricating oil at a very low cost to the consumer to meet competition in price.

Table 1. Physical Properties of Oils Used in Tests

Oil No	Type	Body Rating	Series of Tests Used	Date Purchased	Specific Gravity at 60/60°F.	Flash Point °F.	Fire Point °F.	Pour Point °F	Carbon Residue %	Viscosity Saybolt Second		
										100°F.	130°F.	210°F.
1	Paraffin	Medium	1	June '25	876	450	505		.75	321	158	57
2	Asphalt	Medium	1	June '25	927	340	370			400	163	52
3	Asphalt	Heavy	2	June '26	939	360	405		29	655	230	60
4	Paraffin	Heavy	2	June '26	883	427	470		805	410	200	60
5	Asphalt	Heavy	2	July '26	982	375	420	0	207	470	195	55
6	Paraffin	Heavy	2	July '26	879	450	505		366	334	165	57
7	Asphalt	Heavy	3	June '29	.938	365	425	5	07	553	215	56
8	Paraffin	Heavy	3	June '29	.882	460	510	40	90	756	357	83
9	Asphalt	S A E 40	4	March '31	939	400	450	15	375	1244	400	83
10	Paraffin	S A E 40	4	March '31	884	450	505	15	88	627	302	82
11	Paraffin	S A E 40	4	April '32	.8844	440	485	25	80	615	260	70
12	Asphalt	S A E 30	4	August '32	.9303	400	445	5	19	702	264	61
13	Paraffin	S A E 30	4	August '32	8811	435	490	15	56	431	204	63
14	Paraffin*	S A E 30	4	August '32	905	425	480	0	35	645	264	69
15	Asphalt	S A E 40	5	August '31	.9328	415	470	5	34	1009	340	68
16	Paraffin	S A E 40	5	August '31	.887	475	520	0	85	649	285	74
17	Asphalt	S A E 40	6	May '32	.923	405	475	10	55	1505	565	88
18	Paraffin	S A E 40	6	May '32	.8844	425	485	15	85	685	270	66
19	Asphalt	S A E 40	6	June '32	9273	395	440	5	30	820	300	65
20	Paraffin*	S A E 40	6	June '32	9036	445	495	5	.95	950	360	78
21	Paraffin	S A E 40	6	June '32	8816	445	505	15	80	670	270	66

This same arrangement exists in other companies; for instance, oils 12 and 15 are the main "stock in trade" representing asphalt base oils of different "body." Oils 13 and 21 are sold to those demanding a paraffin base oil while oil no. 19 is the inferior asphalt base lubricating oil, not recommended, but sold to meet competition. Oils nos. 14 and 20 were of one brand and classified as a mid-continent paraffin.

DETAILS OF ANALYSIS OF CRANK-CASE OILS

The underlying principle governing all of the tests has been to compare the two general types of oil, either by running the two oils in two separate engines where available, as in series two, or by alternating the oils on consecutive runs in the same engine. The same principle was carried out in analyzing the used oils As a rule, five samples of one type of oil were always analyzed with five similar samples of the other type This prevented any favor to one oil over another. With the exception of the tests for carbon residue, for distillation, and for iron content, the physical properties of the oils were determined according to specification of the American Society for Testing Materials.

THE CONRADSON CARBON RESIDUE TEST

Years of experience with the apparatus for this test have shown that unless an unusually skilled operator is in charge, results may vary 10 per cent or more In fact, such errors very often exceed the actual difference that exists between succeeding oil samples of a single run. Accuracy in comparing two oils by this test requires exact dupli-

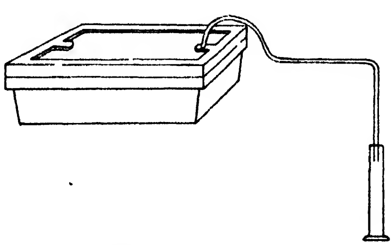

Figure 1. Gas tight container for heating ten samples at one time in making carbon residue tests.

cation of the heating period, which lasts approximately 45 minutes. This was provided for by making the carbon residue test on at least ten samples of oil, five of each type, at the same time. A cast-iron container (Figure 1) large enough to hold ten crucibles was provided with a gas-tight cover and gasket A ⅛" pipe attached to the cover was used to condense the vapors and conduct them to a glass graduate.

A log of each test showed that too slow or too rapid heating during distillation caused wide variations in the carbon residue value. After a few trials, the proper time-temperature control of the Westinghouse B-22 automatically controlled oven was determined. This relationship has been well established by check tests.[5] The results obtained have been very satisfactory, not only because of the speeding up by running 10 samples at a time, but also because of the high degree of accuracy assured, even when considering the small changes occuring in carbon residue from sample to sample.

DISTILLATION TEST

Certain changes were made in the standard apparatus described under A S T M designation, D-86-30, for distillation tests for gasoline, naptha, kerosene, and similar petroleum products. The revised apparatus is shown in Figure 2 A vacuum was applied at the collecting end by inserting a double-holed rubber stopper in the collecting graduate One hole was connected directly to the outlet end of the condensing tube by a suitable rubber stopper and glass tube. The other outlet of the collecting graduate was connected with the vacuum source through a vacuum bottle which acted as a trap to keep water from backing up A water aspirator was used to supply the vacuum

The standard method of heating the Engler flask over a gas flame or an electric hot-plate gave rise to three undesirable conditions:

1 The vapors condensed on the neck of the flask and thermometer bulb and dropped back without passing over.

2. Excessive boiling or foaming occurred in the flask in the distillation of used oils.

3. Cracking of the oil occurred prematurely

[5] Thesis by Kenneth M. Day, "Comparative accuracy using Conradson apparatus with gas heat, Skidmore crucible electrically heated, filtration through Alundum crucible, and the above test method." State College of Washington

All of these conditions were eliminated, as shown in Figure 2, by insulating the neck to a point above the take-off, or above the thermometer bulb, and by enclosing the flask in an electric heater which applied heat evenly over the bulb to a point above the liquid level. In this way more nearly true vapor temperatures were recorded. The current input to the heater was regulated in exactly the same manner in all distillation tests, assuring uniform heat application.

As each test progressed the oil vapors when condensed became more and more viscous and the time lag between temperature reading and recording the quantity at the graduate increased. This was reduced by applying heat at a certain rate to the condenser cooling water as the distillation progressed. However the condensing water was kept sufficiently cold to ensure that all vapors were condensed.

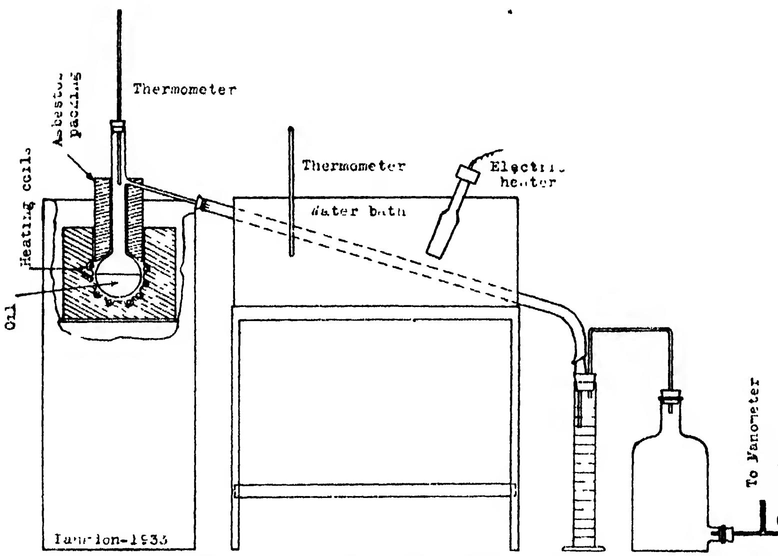

Figure 2. Apparatus specially designed for making uniform distillation tests.

DETERMINING WEAR BY ANALYSIS OF THE IRON IN THE OIL

If the ability of one type of lubricating oil to prevent wear is greater than that of another type, then, under similar conditions of

operation of the engine, an analysis of the different used oils for their iron content should indicate their relative lubricating value. On this basis, also, an iron analysis of samples of the same oil from the crankcase from time to time should give a reliable indication of the rate of wear taking place.

After several years of experimental work, a satisfactory method was developed for making iron analysis of oils, which would give consistently reliable results. It must be remembered that the iron that is worn off an engine is in extremely fine particles. Pictures have been taken of films of used crank-case oil, magnified 1000 diameters, in which the largest particles observed of any substance present were less than .0002 inches across. For some samples, the iron in a 10-gram sample of used oil as tested, was a quantity as low as .00001 gram of iron per gram of oil. This value is too small to weigh except with super-sensitive balances, and obviously the method of centrifuging and weighing was not practical. Ultimately a chemical method of analysis was worked out and adopted.[6]

At the conclusion of the test for carbon residue of a given oil, carbon, iron, and other metal particles, along with foreign material such as dirt, remain in the crucibles. The problem is to determine the true iron content of this residue. The crucibles, following the carbon residue test, are ignited for one half hour at 1500° F. The carbon is oxidized and passes off. The iron is also oxidized, but it remains in the crucible, although just what form it takes is not certain.

Following ignition, the crucibles are weighed to tenths of milligrams. This includes the weight of the iron oxide plus the weight of other metallic oxides, silica and alumina that might be present.[7]

Following weighing hydrochloric and nitric acid are added to the crucible, covered with a watch glass and placed on a hot-plate with controlled heat until the iron is dissolved. The contents of the crucible are then poured into a 250 cc. beaker and the crucible and cover glass are carefully washed with distilled water so that no traces of the dissolved iron solution are lost.

Twenty cc. of 18 normal sulphuric acid are added to the beaker and allowed to fume slightly on a hot-plate. The content of the beaker is next transferred to a 100 cc. sugar flask with a careful washing with di tilled water, and diluted to 100 cc.

Standard solutions, of 1000 cc. each, of varying strengths are made up in like manner, except that known quantities of pure iron are added and dissolved.

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[6] The writer desires to extend full credit to Dr. Ralph W. Gelbach of the Department of Chemistry, State College of Washington, for his interest and assistance in developing a chemical test sufficiently sensitive and accurate for analyzing lubricating oils for iron content.

[7] Engines with cast-iron pistons were used in all cases except that one tractor was equipped with aluminum alloy pistons.

The final determination is made by the colorimetric method. An iron standard of approximately the proper strength is selected and a measured quantity placed in the cell of the colorimeter. The same quantity of the sample solution is placed in the other cell of the colorimeter. Potassium thio-cyanate is added to both cells by means of a pipette, the solution stirred and the cells transferred to the colorimeter for reading.

The potassium thio-cyanate causes the solution to turn red, the density of the color depending upon the iron content of the solution. The colorimeter determines the depth of solution in each cell necessary to match their color. By ratio of depths of solution and the known iron content of the standard solution the quantity of iron in the unknown sample is readily determined.

Based on the above outline, a reliable laboratory technique has been developed so that samples of oil can be readily and accurately analyzed for iron content. Check analyses made from time to time have verified the accuracy of this technique

SUMMARY OF RESULTS OBTAINED

The relative wear occurring between the two types of oil, paraffin and asphalt base, for all of the series, is shown in Table 2

Table 2

Series Number	Averages of total wear in grams—asphalt base	Averages of total wear in grams—paraffin base	Ratio of wear asphalt to paraffin
2—(4 runs per car, 800 miles per run with 2 cars)	845	.47	1 80—1
3—(6 runs, 500 miles per run, 1 car)	99	63	1 57—1
4—(7 runs, 12 hours each, laboratory)	.75	.395	1.90—1
5—(4 runs, 20 hours each, harvester engine)	8 4	6 7	1.25—1
6—(11 runs, 40 to 60 hours, 2 Caterpillar tractors)	28.0	24 1	1 16—1
Weighted average of all tests*			1.49—1
Weighted average of auto and lab tests			1.76—1
Weighted average of farm tests			1 18—1

* In determining the weighted average wear for all tests, the individual engines, which were different in size and construction details were rated in terms of relative total piston surface traversed in a given period of time It has been determined in these tests that approximately 80% of the iron appearing in the samples was worn from the cylinder walls, piston rings and from the piston surfaces The relative rate of wear occurring in the laboratory and in the field was determined upon this basis of engine rating. The results should show without question the serious effect of dust and foreign material in field operation

From Table 2 it will be seen that the harvester and tractor engines show a far greater rate of wear than the automobile and laboratory engines. The engines used in these tests were not of the same rating, speed or number of cylinders. An approximate factor has been arrived at for each engine, which, when applied to the individual engines will correct for these differences. Correcting for both the length of run and the difference in engine characteristics, wear proceeded in the harvester engine, 7 times more rapidly than it would have occurred under laboratory conditions. Likewise in the tractor engine wear proceeded at 18 times the laboratory rate. This increased rate of wear can be explained by the severe dirt and dust conditions under which the tractors operate when compared to operation under laboratory conditions.* Additional proof that abrasive dust particles are responsible for the rapid wear can be found in three observed facts. 1st. Wear increased with the dryness of the season In the first part of the season when the ground was still damp from the spring rains, a relatively small wear occurred in the individual runs 2nd. In the oil analysis procedure, it was observed that high iron content in the individual samples was coincident with high alumina and silica content (dust).[8] 3rd. Tractors used on Palouse wheat farms often require a rebore and refitting of pistons and rings each year

DISCUSSION OF RESULTS

In Figures 3, 4, 5, 6, and 7 are given in graphic form, all the data pertinent to these tests While each set of data shown in each figure has its value, the attention of the user will center on the curves for relative iron wear, since these indicate the relative life of his power unit.

* The tractors were provided with air cleaners for the air to the carburetor and in addition both had protected breather connections to the crankcase. The harvester engine had a protected carburetor air inlet

[8] Observations and calculations have been made to determine what portion of the iron in the sample was due to ferrogenous earth, and was determined to be a negligible percentage

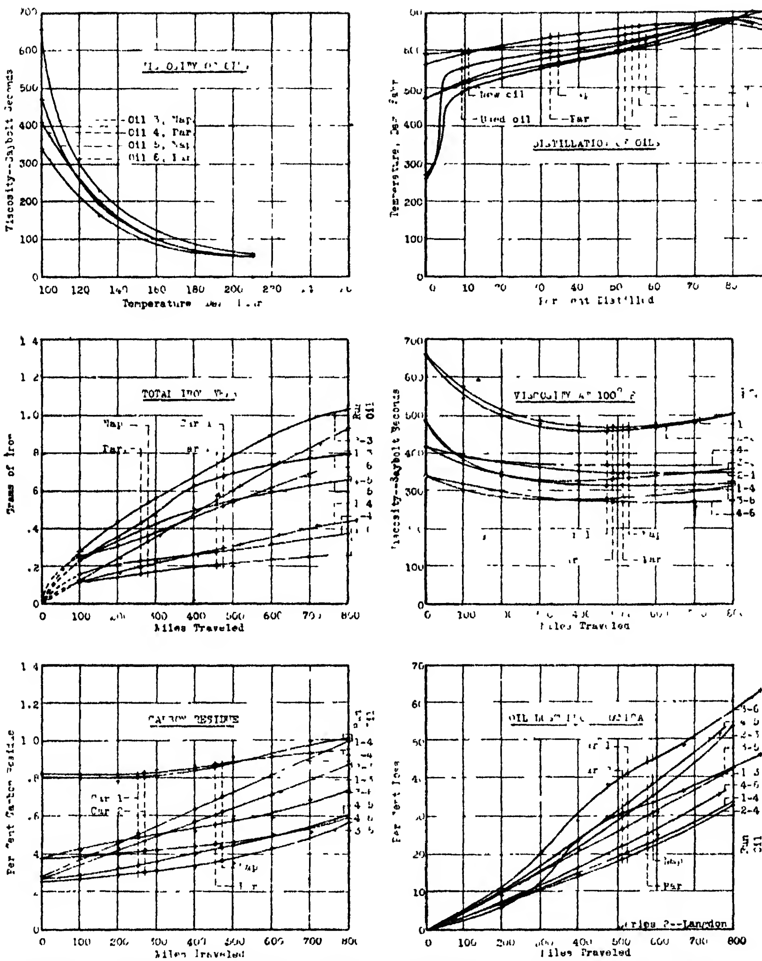

Figure 3. Two Oakland coaches traveling 30 MPH on relatively clean highways.

Note that abbreviation "Par" represents oils having a paraffin base, while "Nap" represents oils having an asphalt, or napthene base.

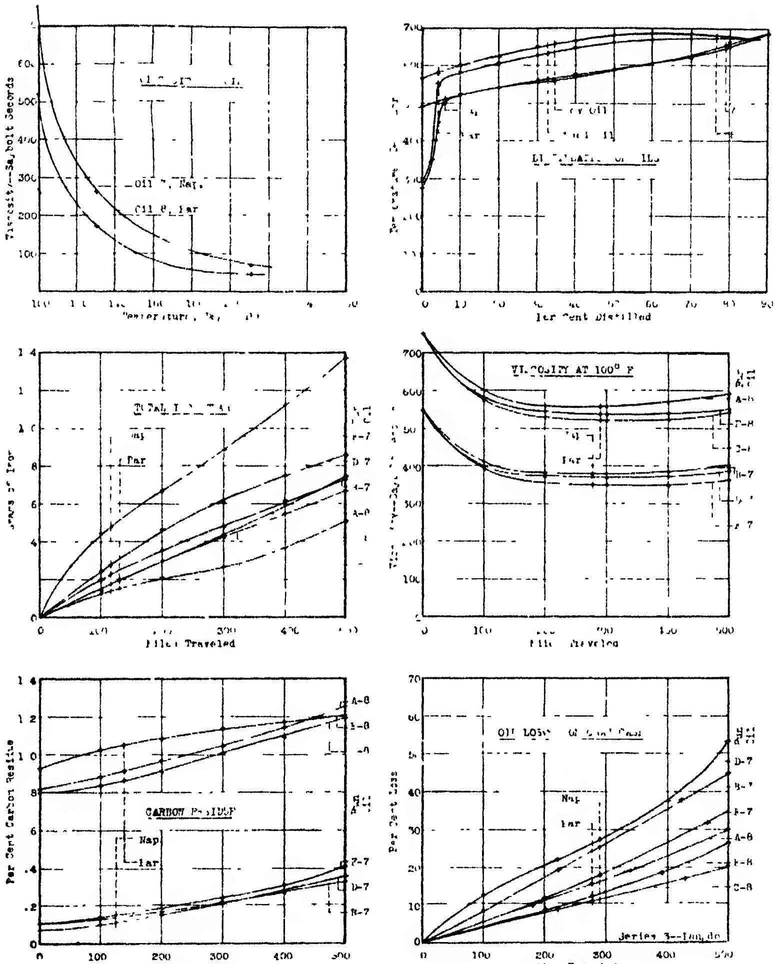

Figure 4. Chevrolet coach traveling over gravel highway which was sometimes dusty

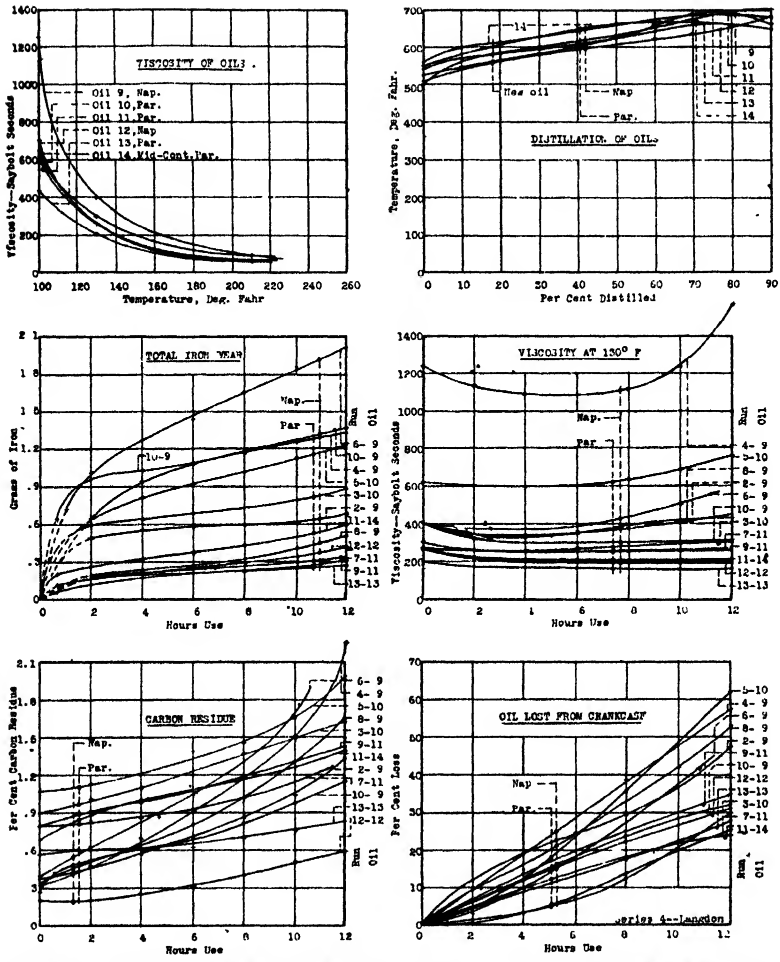

Figure 5. Chevrolet engine from car used in Figure 4, mounted in laboratory and operated under carefully supervised conditions.

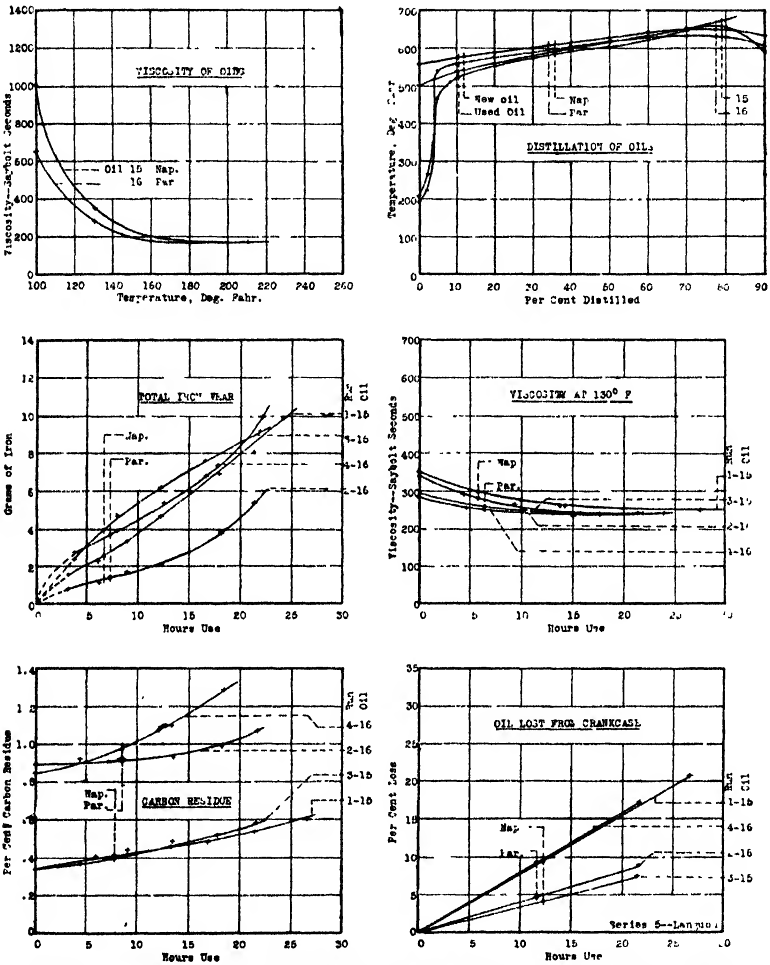

Figure 6. Case Combined Harvester engine operated on harvester in the field.

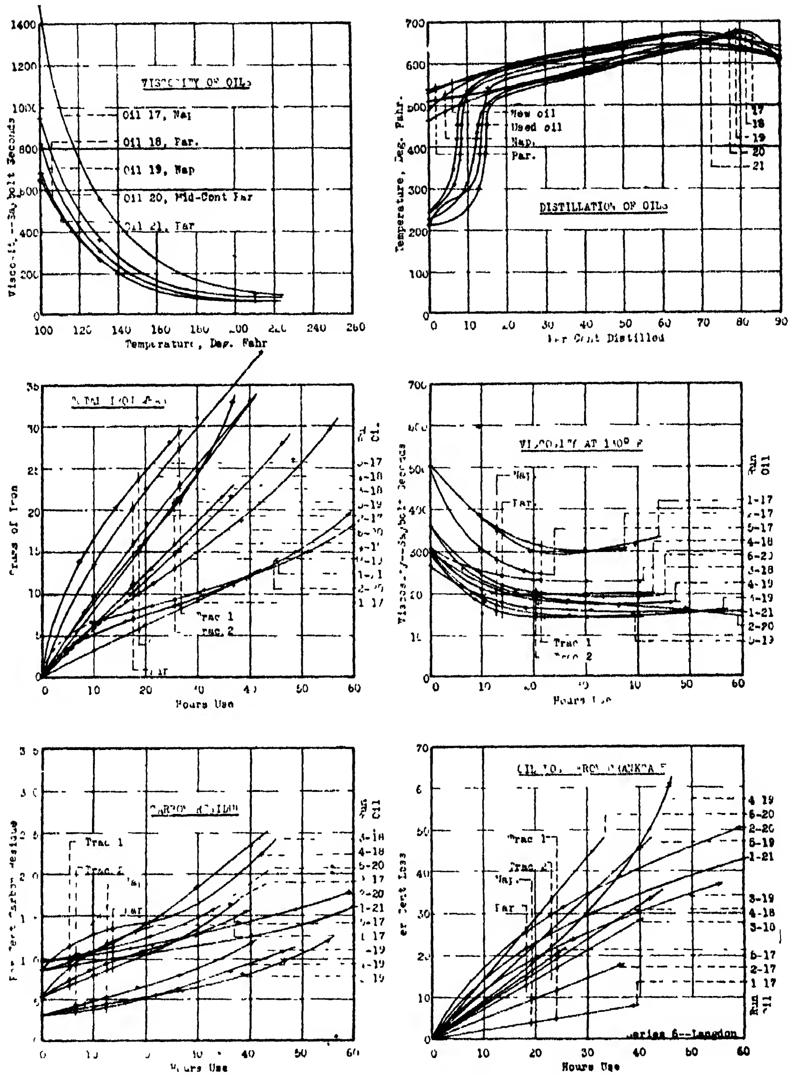

Figure 7 Two Caterpillar Tractors operated on different farms in the Palouse Country, plowing and seeding.

Viscosity[9]

During the first half of each test, there was a general decrease in viscosity of the oil. During the second half, in the majority of cases, the viscosity of the asphalt base oils increased, while the viscosity of the paraffin base oil remained nearly constant. The decrease in viscosity during the first half of each test was greater with the asphaltic oil in practically all runs In the tests on the farm tractors, dilution caused the oil to "thin out" during practically the entire period of operation with both types of oil.

Carbon Residue[10]

The asphaltic oil has, in general, a low initial carbon residue, while the paraffin base oil has a high value In a majority of all runs, the carbon residue value has increased more rapidly with use for the asphaltic oils than for the paraffin oils. On a percentage basis this has been true in all cases The carbon residue value of an oil is not

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[9] Viscosity tests follow A S T M designation D88-30

From the standpoint of performance, viscosity is a very important characteristic of any lubricating oil, indicating its "body." The viscosity of an oil is an indication of its suitability for specific purposes Oil of low viscosity would be suitable for a sewing machine, cream separator, or other high speed machinery, and unsuited for heavy, low speed machinery A new automobile with close-fitting parts would require a "light" bodied oil of low viscosity, while a badly worn engine would require a high viscosity oil, ordinarily termed "heavy" Viscosity may help to indicate the source of an oil Paraffin base oils have a lower viscosity change with temperature than asphalt base oils Under given conditions of operation, that oil is superior which shows the least change in viscosity Viscosity in terms of Saybolt standard is recorded in seconds at 100° F, 130° F, and 210° F For instance, it requires 600 seconds for 60 cc of a certain oil at 100° F to flow through the orifice tube of a Saybolt standard viscosimeter In order to assure uniformity in the trade, oils are now rated S A E 20, 30, 40, etc, instead of terming them light, medium, or heavy

[10] Carbon residue by A S T M designation D-189-30 This test consists of subjecting a 10-gram sample of oil in a weighed crucible to temperatures sufficiently high to distill away the volatile oil. Heated in a nearly oxygen-free atmosphere, the result is a coke-like material in the bottom of the crucible, and is called the carbon residue. Extensive tests by other investigators have shown that the carbon residue test is a fairly reliable indication of the tendencies of an oil to form carbon in the combustion chamber, also that the carbon forming tendencies are superior for asphalt than for paraffin base oil * According to a paper by R E Wilson and D. P Barnard,† "While the significance of this test has been the subject of considerable dispute, recent evidence indicates rather clearly that when using the same engine under carefully controlled conditions the carbon deposit in the combustion space is a function of this carbon residue value of the oil, though the carbon deposit increases much less rapidly than in direct proportion to this value Of course, if the oils have different viscosities at the operating temperatures the one with the lower viscosity tends to pass the rings in larger quantities and thus affect the amount of carbon formation Furthermore, in actual service the condition of the engine and particularly the type and fit of the rings as well as the changes in mixture ratio, operating temperature, oil viscosity, etc, will obscure or outweigh ordinary differences in carbon residue between two different oils"

* Carbon Deposits from Lubricating Oils, Ind. & Eng Chem., Vol. 21, P 904 Also Carbon Deposits with Heavy Duty Engines, S.A.E Journal, November, 1929

† The Significance of Various Tests Applied to Motor Oils—Proceedings of the A. S. T M Vol 28, Part 2, P. 678 1928

an indication of its ability to prevent wear. Paraffin base oils with both high and low carbon residue have given better lubrication than the asphaltic oils with initially low carbon residue values.

Distillation[11]

Distillation curves show a characteristic difference between the two types of oil. The cracking point for the asphalt base oil occurred, as a rule, at from 85 to 95 per cent distilled. For the paraffin base oil, this occurred at from 70 to 80 per cent. Dilution of the crank-case oil in the laboratory engine, where there was only one start, and the engine closely fitted, varied between 1 and 3 per cent. In the tractor engines, which were somewhat worn and where there were perhaps twelve starts to a run, the value was as high as 14 per cent.

Gravity Test

The gravity of an oil is usually read in degrees A.P.I. (American Petroleum Institute Gravity Scale.) The values are corrected to degrees A P.I. at 60° F temperature and subsequently changed to "Specific Gravity 60°/60° F" This means that the oil has a certain specific gravity at 60° F when referred to water at 60° F. This test has no value to the user except as a possible means of identification. As a rule a Pennsylvania paraffin base oil has a lower specific gravity than an asphalt base oil of the same viscosity at 130° F. A mid-continent paraffin base oil, however, may have a specific gravity little different from an asphaltic oil One familiar with the trade, can as a rule

[11] The distillation test of lubricating oils under vacuum is not considered a standard test. However, it was used in this study to indicate the characteristic difference between a paraffin and an asphalt base oil, to determine the relative cracking point of the two types, and to measure the extent of dilution occurring during the use of the oil According to Livingston, Martin, and Morley,* the relative volatility of the oils before cracking begins is an indication of the relative tendencies of the two types to deposit carbon.

Tests made in this study show that cracking begins at approximately 70 per cent distilled for the paraffin oil, and from 85 to 90 per cent for the asphalt base oil It is believed that this test is of value in identifying the source of an oil, as well as to indicate the extent of dilution during use.

A paraffin base oil for automotive purposes is, as a rule, a blend between a light "straight run" distilled oil from paraffin crude and a properly refined heavy cylinder stock which is a residue from the distillation of the same crude. Any further attempt to distill the cylinder stock results in the cracking of the oil. This blending of the paraffin oil results in a distillation curve (oil no. 4, figure 3) that is comparatively flat The point on the curve where the temperature starts to decrease with increasing quantities distilled is considered to be the point where "cracking" begins

An asphalt base lubricating oil is the result of a straight distillation process. (oil no. 3, Figure 3).

* Carbon Deposits with Heavy Duty Engines, S. A. E. Journal, Nov., 1929.

identify a Pennsylvania paraffin base lubricating oil when he takes into account other factors which influence this value.

Flash and Fire Tests, A S T M Designation D92-24

These tests are usually made only on a new oil, and have little value except to identify its source, and then only when considered together with other properties In the tests made with the Cleveland open cup apparatus, the paraffin base oils as a rule registered the higher flash and fire points

Cloud and Pour Tests, A S T M Designation D97-30

These tests are of value only to indicate the temperature during very cold weather at which the oil in the crank-case may become too thick to flow when the engine starts This would result in burned-out bearings and scored cylinders The viscosity of an asphalt base oil increases rapidly as the temperature approaches zero Fahrenheit This may become 200,000 or more in Saybolt seconds, while a paraffin base oil would be approximately 10,000 seconds, with both oils having the same viscosity at 210° F

However, the paraffin base oil because of the wax contained in the oil will solidify at a low temperature depending upon the quantity of wax contained[12] If the oil actually freezes in the crank-case in extremely cold weather, damage to the engine may result[13]

The paraffin base oil has a better characteristic for starting in cold weather unless it becomes actually frozen in the crank-case because of the wax present The asphalt base oil will not freeze under like conditions, but does become extremely viscous, thus increasing the load on the starter and battery

Oil Consumption

Oil consumption as indicated by loss of oil from the crank-case includes loss by pumping and burning, by distillation, and by leakage. Table 3 shows the average loss of oil for each of the series of tests

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[12] Improved Paraffin Base Lubricating Oils, Ind & Eng Chemistry Vol. 23, No 12, December, 1931

[13] Wilkins, Oak and Barnard "Motor Oil Performance at Low Temperatures," S A E Journal, Vol 22, P 213

Table 3

Test Series	No Runs Each Oil	Approx Hrs Each Run	Average Per Cent Oil Consumption Asphaltic	Paraffin
2	4	26	48	40
3	3	22	45	26
4	6	12	45	34
5	2	25	11	13
6	5	50	30	37
Weighted average of all tests			38	33

CONCLUSIONS

It should be remembered that the foregoing study is in the field of automotive lubrication only, and that it covers what are considered to be a few typical oils representing the asphalt and paraffin bases The oils chosen are those that are in direct competition throughout most of the United States and are representative of many other oils sold

This series of tests, while not as extensive as other tests upon the change in physical properties of lubricating oil during use, has gone deeper into the heart of the problem than any reports so far published have indicated Wear of important parts of the automotive engine determines the maintenance cost which is, as a rule, greater than the difference in cost between high and low grade lubricating oils.

As a result of this study the following conclusions can be drawn:

1. To the consumer the so-called physical property tests of lubricating oils are of value chiefly for the purpose of identification, and for making certain that the oils purchased are up to the manufacturer's specifications

2. Viscosity tests are of value in adapting a lubricating oil to the needs of an engine, and for the identification of oils, but do not necessarily indicate the lubricating value of an oil. A paraffin base oil, as a rule, maintains a more uniform viscosity with use than does an asphalt base oil.

3 Distillation tests and flash and fire tests are useful for identification and refinery control, but it is doubtful if there is any direct relation between these tests and lubricating value. Cloud and pour

tests may be important for selecting oils to be used in extremely cold weather, but are not a guide in determining lubricating value for normal operation.

4. An oil testing high in carbon residue does not necessarily possess inferior lubricating properties The foregoing tests indicate that oils with high initial carbon residue have shown superior lubricating ability, although this study would seem to indicate that there is no direct relation between the two The carbon residue test should be used only as a means of refinery control and identification Where other investigators have shown that the carbon residue values influence the rate of carbon deposition in the combustion chamber, the foregoing tests would seem to indicate that other influences, such as leakage past the rings, were much more important in forming carbon deposits

5 Operation under dusty conditions, such as farm work, reveals the desirability of dust proofing such engines In these tests excess wear due to dust reached as high as 2000%, and consequently the comparative value of any lubricant was accordingly diminished However, even in this case somewhat less wear was shown for the paraffin base oil

6 In the comparative tests, leakage and pumping losses were greater by as much as 6% with the asphalt than with the paraffin base oils

7 In automobile, laboratory, and field operation of the automotive engines used in these tests, an average of 54% greater wear of the working parts took place with typical asphalt base oils than with typical paraffin base oils

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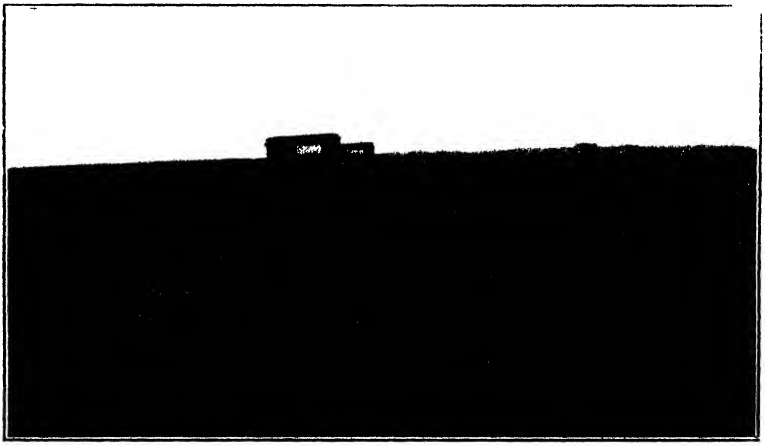
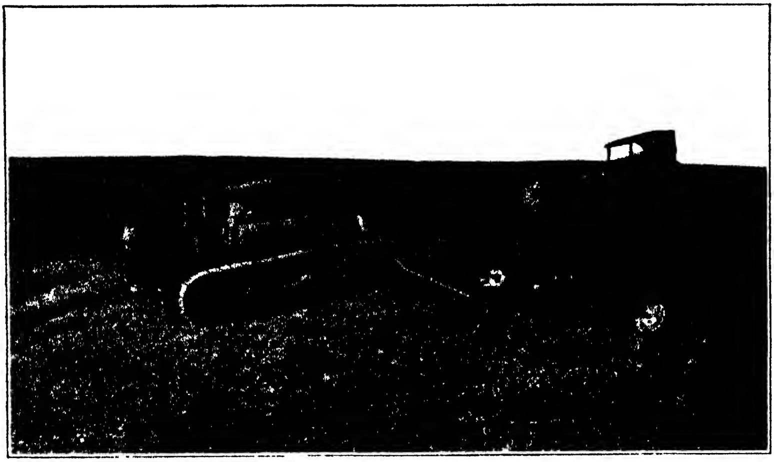


Extensive lubrication tests were conducted on two identical cars operated over different kinds of highway surfaces. Different lubricants were alternated between the two cars, thus affording comparison under identical conditions.



Tests on tractors doing farm work emphasized the need for adequate dust filters. Under dusty conditions, the wear on engine parts due to dust getting into the engine may easily overshadow the question of relative value of lubricants.

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Small Scale Methods of Placer Mining and Placer Mining Districts of Washington and Oregon

by

Guy E. Ingersoll

School of Mines and Geology

ENGINEERING BULLETIN NO. 43

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H. V. Carpenter, Director

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc

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The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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Small Scale Methods of Placer Mining and Placer Mining Districts of Washington and Oregon

by Guy E. Ingersoll

INTRODUCTION

This bulletin supersedes Bulletin 40 on hand methods of placer mining. Ten thousand copies of Number 40 were distributed and it is no longer available. In addition to the description of hand methods of placer mining, this bulletin describes a few of the methods and power machines used for placer mining, especially for the recovery of fine gold that is lost in ordinary sluice boxes The author does not attempt to describe or mention all of the machines on the market to recover fine gold, but mentions a few that have been advertised in the technical mining publications We have not tested any of these machines and do not guarantee results on any of them

In times of depression gold mining is a thriving industry There is a ready market for the gold The gold recovered in mining operations adds to the wealth of the country Placer mining takes the unemployed away from the cities into a better environment

During the summer of 1932 there was a big rush of people, men, women and children, to the streams of the Pacific Northwest in search of gold It is expected that this will be repeated in 1933

This bulletin is dedicated to the unemployed of the State of Washington If it will help anyone to recover enough gold to provide food, shelter, and clothing, it will have served its purpose

Warning:

All persons going into the woods and hills of the Pacific Northwest should beware of the ticks found in this region, especially in the Bitter Root Mountains of Montana. The bite of these ticks may cause Rocky Mountain spotted fever. They are found from about April first to July first. People can guard against the danger of tick bite by having an innoculation made with a vaccine furnished free by the

Federal Government's Rock Mountain Spotted Fever Laboratory at Hamilton, Montana. The innoculation should be taken in April. Your local physician or health officer may obtain this vaccine and give the innoculation.

GOLD

Physical Properties

Gold is distinguished from other common metallic elements by its beautiful characteristic yellow color which it preserves untarnished on exposure under nearly all conditions. Pure gold has a high metallic luster. It is heavier than any common metal, being 1½ times as heavy as lead and nearly twice as heavy as silver, bulk for bulk. The pure metal is somewhat harder than lead but softer than copper, silver, platinum, zinc or iron. Gold is readily attacked by mercury (quicksilver) and dissolves in that metal, forming amalgam. If the liquid amalgam is squeezed through chamois skin, a yellow pasty mass remains. Gold is unattacked by any one of the simple acids, save selenic, but dissolves in any mixture in which chlorine, bromine, or iodine is liberated. It also dissolves in potassium cyanide solutions in the presence of air.

In nature, gold usually occurs native, that is uncombined. The mineral most commonly found with gold in lodes is iron pyrites, a yellow sulphide of iron. Others are copper pyrites, arsenical pyrites, zinc blende and stibnite. At the surface of the ground, where the lodes are weathered, limonite, a yellow oxide of iron, is the best indicator of gold. In placers, magnetite (black iron sand) usually occurs.

Occurrence

Gold occurs in very small quantities in almost all rocks. Gold is seldom found in large masses of rock in amounts which can be mined at a profit. It is usually found in quartz lodes or veins, or from deposits derived from them called placers.

PLACER DEPOSITS

Origin of Placer Deposits

As a land surface is worn away, gold contained in veins or lodes tends gradually to become concentrated at the surface. This is shown

in Fig. 1. Some of it may remain practically in place. As erosion goes on, the gold-bearing rock will gradually settle down-hill. As erosion is continued further, however, the gold ultimately finds lodgement in streams together with sand and gravel. These are placer deposits. The gold sinks to the bottom and remains on bedrock, especially in joints and seams or in low places in the bed. As gold is about six or seven times as heavy as rock, it will sink, except the very finest dust, which may be carried away. The coarser gold generally remains in gulches and creeks near its source, forming gulch and creek gravels; the finer gold may be carried to rivers and supply gold for river gravels; some gold may be carried even to the sea.

Location of Placers

Placers formed in gulches, in beds of rivers, or on the sea shore may be elevated by general uplift of the region to levels above the present drainage lines. Some deposits worked for placer gold are far above the present streams

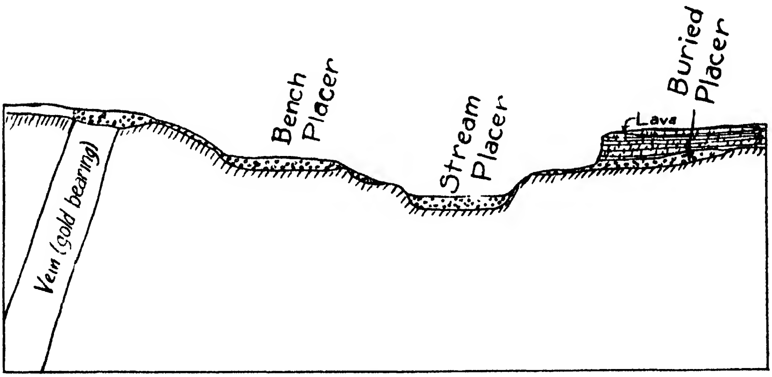


Figure 1
Sketch showing locations of placer deposits in relation to parent vein.

Buried Placers

Placer deposits may be buried under later deposits. Lava flows have often covered placer deposits. The later streams will take new courses and when they cut through the lavas may expose the old placer deposits on the hillsides.

There is a strong tendency for gold to work downward in gravels. It may halt at a stiff clay seam in the gravel bed, or it may descend to the bedrock.

Characteristics of Placer Gravels

The size of gravel varies from fine sand to boulders of several tons. The size of gravels affects the amount that can be washed or concentrated with a given volume of water.

The shape of gravel may be round and water-worn, sub-angular or angular. Some gravels consist entirely of rounded stones with little sand; others, of stones embedded in clay. Sometimes this gravel is cemented. Angular pieces and crystallized gold, occasionally found, indicate nearness to the parent vein or lode.

Values in gravel are expressed in cents or dollars per cubic yard, or square foot or square yard of bedrock.

Size of Gold Particles

The size of gold particles found in placer deposits varies greatly, ranging from large nuggets weighing several ounces or even pounds, to fine flour gold requiring 885,000 colors (gold particles or grains) to make an ounce or 500 colors to 1 cent The various sizes of gold particles have been classified by Young as follows:

Nuggets:

Coarse gold—that which remains on a 10-mesh screen (10 openings per linear inch).

Medium gold—that which remains on a 20-mesh screen but passes through a 10-mesh screen (average 2,200 colors per ounce).

Fine gold—that which passes a 20-mesh screen and remains on a 40-mesh screen (average 12,000 colors per ounce).

Very fine gold—that which passes a 40-mesh screen (average 40,000 colors per ounce).

Flour gold:

170 colors to 1 cent (314,500 per ounce)

280 colors to 1 cent (436,900 per ounce).

500 colors to 1 cent (885,000 per ounce).

Pure gold is worth $20.67 per ounce. Gold as it occurs in nature is usually alloyed with varying proportions of silver, and the average

value of placer gold may be roughly taken at about $18.50 per ounce. Medium gold as above defined is therefore worth about 84/100 of a cent per color, and fine gold about 15/1000 of a cent per color.

Gold in the coarser sizes is much easier to recover. Fine or flour gold is apt to float off with the light material, either free or tied up in fragments and fine pieces thereof.

Prospecting Placers

Before installing equipment of any size, a placer deposit should be prospected to determine whether or not it will be worth working by primitive methods. Inasmuch as this pamphlet describes the simpler methods, the discussion to follow will be on the assumption that the gravel is shallow.

The first search for placer gold is usually confined to stream beds, their bars, and to tributary gulches, since, as previously pointed out, the streams and their tributaries are principal agencies in the formation of placers Even though the most valuable deposits may be in benches high up on the slopes, their presence would almost invariably be evidenced by showings of gold along the streams below.

In prospecting along a stream the prospector will pan the gravel at various points, selecting particularly such places as show evidences of concentration of heavy minerals by the presence of black sands. Since the gold and heavy sands will ordinarily be found concentrated on bedrock, the prospector will investigate exposures of bedrock in and along the stream, especially depressions therein where these minerals may be caught. In addition, excavations to bed-rock will be made in the gravels of the stream bed and its bars and along its banks.

In small-scale handwork, prospecting and actual mining, whether by panning, rocking, or sluicing, are conducted together as one and the same operation. That is to say, the deposit is prospected as it is mined, the work being shifted from place to place according to disclosures made during progress of the work; the results of panning are ordinarily used as a guide.

PLACER-MINING METHODS

Placer mining is conducted by both open-cut and underground methods. Underground placer mining, commonly known as "drift

mining," is employed in mining buried placers. Open-cut methods may be classified on the basis of equipment employed, as follows:

1. Hand methods:
    a. Panning
    b. Rocking
    c. Long Toms and surf-washers.
    d. Sluicing, including ground sluicing and "booming."
2. Power Methods:
    a. Power methods of gold extraction
        1. Mechanically operated pan, rockers, sluices and tables
        2. Mechanically operated amalgamators and flotation cells
    b. Power methods of excavation
        1. Drag scraping
        2. Hydraulic mining
        3. Power shoveling
    c. Combined power methods of excavation and extraction
        1. Dredges
3. Dry Placer Mining

Hand methods are applicable to small-scale operations and, since little capital expenditure is required, are suited to the small individual operator or group of operators possessed of only small means. They are in general applicable to deposits of shallow depth having only a shallow covering of barren material.

Pan

The pan and rocker are used by prospectors in searching for placers. The pan is a circular dish with sloping sides with a top diameter of 10, 12½, 16, or 16¼ inches and a depth of 2 to 2⅜ inches. The sides slope 35 to 40 degrees. A gold pan can be purchased in nearly any hardware store A pan should be light, but stiff enough to stand rough usage. The inner surfaces must be smooth, bright and free from grease and rust. If properly cared for, pans of steel meet these requirements, and are cheap. Aluminum pans are light, do not rust, but lack stiffness. Pans of copper, or with copper bottoms and with steel rim are sometimes used. For fine gold which will amalgamate (be wet by quicksilver) the bottom is silver plated and coated with mercury.

Operation of Panning:

A 16-inch pan will hold from 15 to 20 pounds of dirt, depending upon the character of the ground, and a 10-inch pan will hold from 3 to 5 pounds A good placer miner, by continuous washing may in 10 hours pan from ½ to 1 cubic yard, depending upon the amount of water and character of the gravel.

A pan of gravel is placed in water, the gravel thoroughly wetted and stirred by hand to break up lumps of clay, and the larger stones are picked out. The pan, still under water, is then given a shaking or gyratory motion, which brings the light material to the surface and allows heavy particles to settle.

The pan is held tilted slightly away from the operator. The motion of the pan serves to concentrate the gold and heavy minerals around the edge of the bottom of the pan. The washing away of the light material is helped by alternately raising and lowering the far edge or lip of the pan above and below the surface of the water. The pan may be occasionally lifted entirely from the water and shaken vigorously with the usual circular motion to concentrate the gold and heavy sands and to bring the pebbles and fine light material to the top. This material may then be scraped off the lip of the pan with the thumb, thus hastening the operation of panning The panning is continued till only the gold and heaviest minerals remain in the pan. Toward the end of the operation it may be well to finish panning in a tub of water instead of in the stream, since any gold that may be inadvertantly carried away may later be recovered by repanning the contents of the tub The final product is dried and black sand is removed with a magnet Coarse gold can be picked out color by color and fine gold may be recovered by amalgamation with mercury.

Identification of Gold:

With a little experience gold is readily distinguished from the other minerals, the ones which are most deceptive to the novice being pyrite and biotite mica. Pyrite is often mistaken for gold by the novice because of its yellow color. Pyrite is very brittle, however, and can easily be crushed. Gold, on the other hand, is malleable, and when pounded it simply flattens out without breaking. Faces of pyrite crystals usually reflect slight changes of color when turned about in the light, whereas gold looks the same from all angles Sometimes

placer gold takes on a rusty appearance due to a film of iron oxide which obscures its true color and character. As the proportion of silver alloyed with the gold changes, the intensity of the gold color will vary, till in electrum (gold alloyed with upwards of 18 per cent of silver) a pale silvery-yellow color is characteristic. Biotite mica often alters to a bronze color which may give it the appearance of gold. Mica, however, reflects different shades when turned about or viewed from different angles in the light, and if hammered will break up into thin white flakes. The great difference in weight between gold and mica permit their ready separation by panning.

Performance of Panning:

Panning is slow, tedious work. The only tools required are a pick, shovel, and a pan. It is a favorite poor-man's method and is a common temporary method in a new district. The pan is indispensible for testing gravel when prospecting and for cleaning up rocker and other concentrates in large-scale sampling and mining operations.

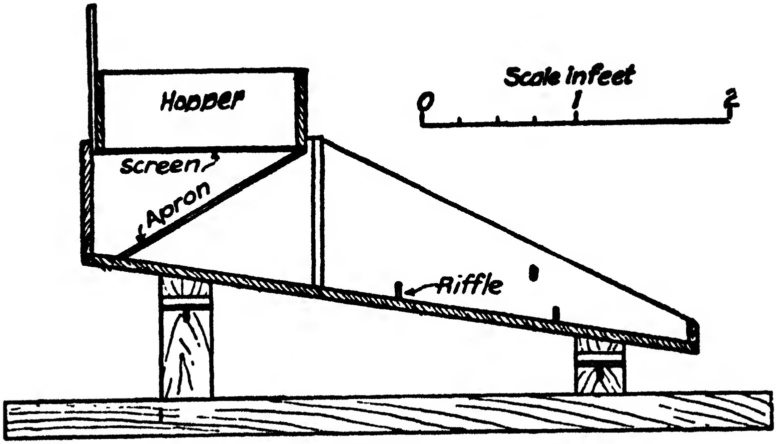
An experienced man can carefully pan about 100 pans in 10 hours, the exact amount depending upon the skill of the panner, the extent to which the gravel is cemented and whether it is clayey or not, and the size of the gold. The ordinary gold pan is estimated to hold 267 cubic inches on the average—or, putting it the other way around, 176 pans are equivalent to 1 cubic yard of material in place. At Fairbanks, Alaska, most miners compute 189 pans per cubic yard. A good panner will therefore pan about 6/10 cubic yard per day, and in order to make $5.00 per day, the dirt would have to average about $10.00 per cubic yard. This would be considered rich gravel today. In exceptional cases a man will sometimes pan 1 cubic yard per day.

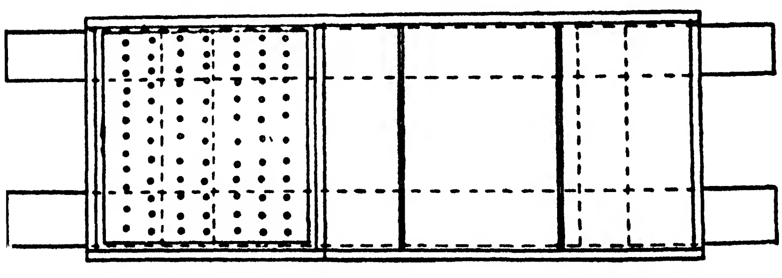
Sampling Placer Deposits:

For large deposits of low-grade placer material which can only be worked profitably by mechanical means involving large capital expenditures, a thorough preliminary prospecting of the deposit is essential. This may be done by means of test pits or drill holes, depending upon the characteristics of the deposit in each case. It is not within the scope of this paper to discuss such operations, but it may be said that the gold pan is an important implement in this connection also.

Rocker

After testing the ground with a pan it may be decided to work the deposit with a rocker. Figure 2 shows a rocker. A rocker sometimes called a cradle or dolly, consists of a box on rockers similar to the old fashioned baby's cradle. The general dimensions may be con-





—From Von Bernewitz "Handbook for Prospectors"

Figure 2
Plan and Elevation of a Rocker.

veniently 48 inches long, 18 inches wide, and 18 inches high. The long sides are cut at a slope from about the center to a height of 4 inches at the front end. In the higher or rear end is placed a hopper or sieve

with a tin bottom, ½ inch holes; under this and sloping toward but not touching the rear wall is supported a frame, holding a canvas apron slightly sagging or a sloping board covered with burlap and riffles. A handle is attached to stand up above the box, by which the apparatus is agitated sideways during operation. It will readily be seen that the details of the dimensions of the rocker may be varied according to the character of the dirt to be treated and the supply of material available.

Figure 3

Rocker in use near Wenatchee. This has been called a "Chinese figure 4 rocker." Note the screen in the top section.

Operation of the Rocker:

In operating the rocker, the sieve is filled with dirt, and water is poured in by a ladle or small stream and the whole rocked. This clears the feed of fine sand and muddy water, when the larger gravel can be lifted out after a final cleaning. The fine material passes through the sieve on to the canvas apron.

Figure 4
Side view of rocker used near Wenatchee. The lower sections have burlap or an old blanket in them held in place by a screen.

Most of the gold is retained on the apron; more is caught on the bottom, which may have cross riffles. Clean-ups are made at intervals, depending on the richness and character of gravel. For saving fine gold, the material on the floor of the rocker must be kept loose and free, and spread evenly. Clayey gravel, or that containing much fine black sand often packs behind riffles and tail piece and requires frequent clean-ups. Before cleaning-up, the material back of the tail-piece is removed, dumped into the screen and re-rocked. The apron is then lifted out and its contents washed into a pan for final concentration.

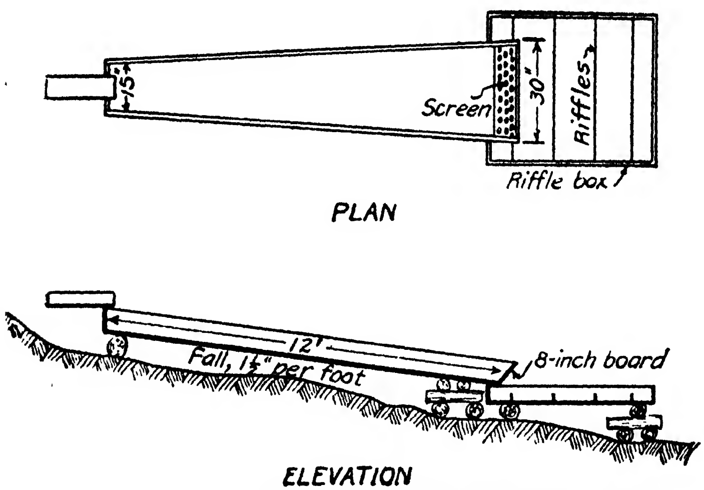
Performance of Rocker:

A rocker may be operated by one man, but two are better. They spell each other in rocking and handling gravel and tailing. Purington gives the work accomplished by two men rocking steadily as 3 to 5 cubic yards per 10 hours.

Long Tom

Long Tom is an open box having at its lower end an inclined screen, punched usually with ½ inch holes. Figure 5, shows a Long Tom.

Running water is carried to the head end by a small flume. Gravel is shoveled into the Tom, and large stones forked out; the fines are worked through the screen and, with the water, fall into a wide-riffle-box set on a flatter grade than the Tom. The gold is caught behind the riffles with, or without, the aid of mercury. The capacity of a Long Tom depends largely upon the amount of gravel which can be shoveled into it. Wilson says that 2 men (1 shoveling to the Tom and 1 working on it) can wash 6 cubic yards of ordinary gravel in 10 hours. At times the Tom is operated by 4 men; 2 shoveling in, 1 forking out stones, and 1 shoveling fine tailing away from end of the riffe-box.



—From Von Bernewitz "Handbook for Prospectors"

Figure 5
Plan and Elevation of Long Tom.

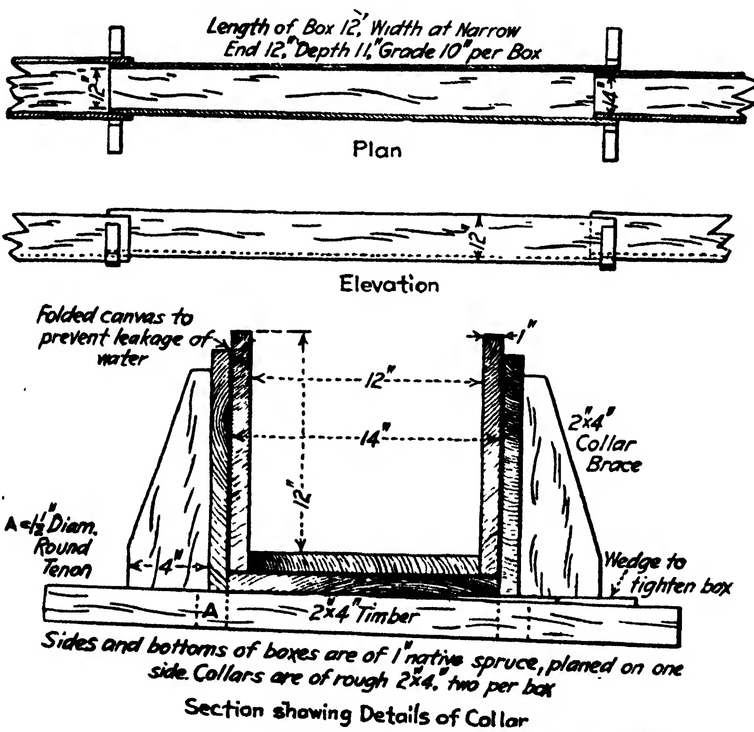
Sluicing

Sluicing is a general term applied to many forms of placer mining. A sluice is an inclined channel or trough, through which gravel is

carried by a stream of water. Stones and light sands pass through and run to waste at the lower end. Gold and other heavy minerals settle to the bottom and are caught in riffles. A riffle is a groove or interstice, or a cleat or block so placed as to produce the same effect, on the bottom of a sluice. Wooden sluices are sometimes called "Box sluices." Inclined ditches, in gravel or bed-rock, are "ground sluices." Riffles in ground-sluices are formed by the natural irregularities of their bottoms.

Construction of Sluices:

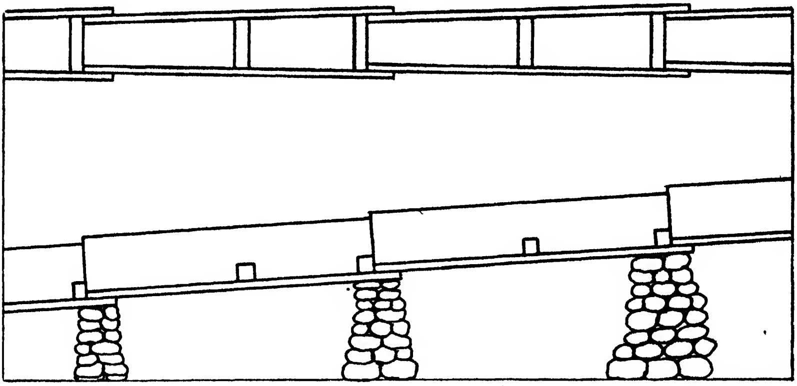
Sluices are made in sections, usually 12 feet long. Each section is called a "sluice-box" Figure 6 shows a typical sluice-box for shoveling-in and other small work. Sides and bottom are 1 inch by 12, 14, or



—From Engineering and Mining Journal

Figure 6
Plan and section of sluice box showing collar.

16 inch boards, rough or planed on one side. The bottom is 2 inches narrower at one end than the other so that adjacent boxes will telescope a few inches into each other. Sluices may rest on bed-rock or be set in ditches, or elevated. Figure 7 shows a sluice-box set up. Sluices are braced laterally by inclined struts. Figure 8 shows a sluice-box with men shoveling in. On the side of the sluice opposite each shoveler is a board against which the gravel is thrown, instead of being shoveled carefully into the sluice. This makes the work more efficient and prevents spilling. A collar may be placed at the junction of each two boxes (see Fig. 6) thus eliminating cross-braces, which obstruct the sluice and interfere slightly with cleaning up. Some sluices may also be made with flush joints, like a flume. (Shown in Fig. 9.) Some operators say this reduces the tendency to clog, but the telescoping box is most used because it is easily erected and moved. These sluices have a short life, but are cheap and well suited to small work. Worn out boxes should be burned and the ashes rocked or sluiced to recover gold which lodges in cracks and joints.



—From Encyclopedia Britannica

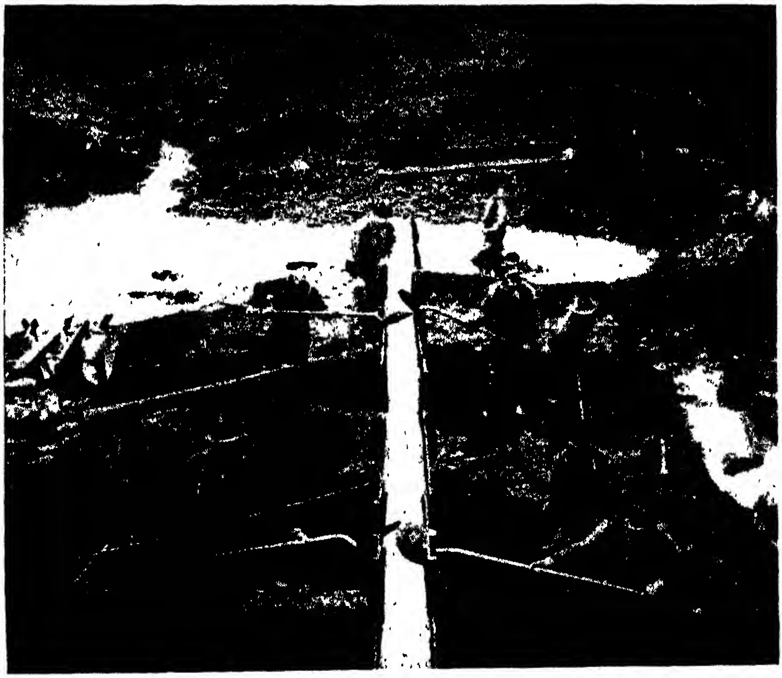
Figure 7
Plan and section showing sluice set up.

Riffles for Small Sluices:

Figure 9 shows forms of riffles commonly used for shoveling-in. The pole riffle is a favorite in Alaska for coarse gold. Transverse (or Hungarian) riffles offer greater frictional resistance, clog more easily,

and cost more than the longitudinal riffle, but is a better saver of fine gold. In a string of sluice-boxes both types are commonly used, the number and distribution of each depending on the operator's fancy. Small riffles are fastened by nails driven into them through the sides of the sluice; as the nails are not driven home, they are easily pulled when riffles are removed for clean-ups. Wedges may be used instead of nails but are troublesome.

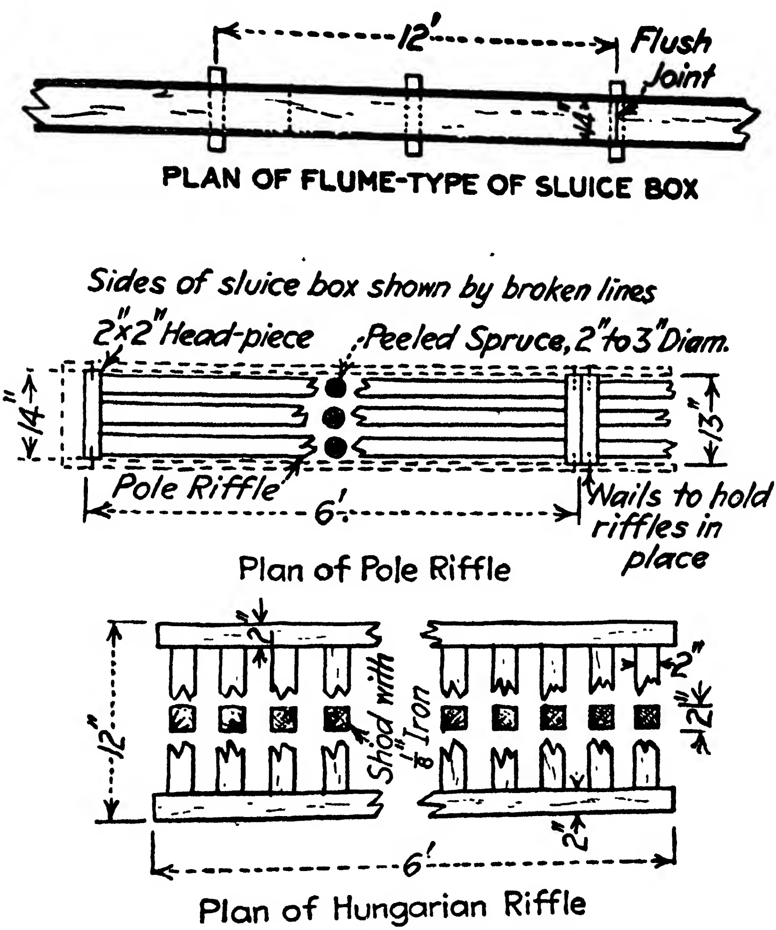
Many different kinds of riffles have been devised by the placer miner. Usually the available material determines the selection Round wooden poles, poles protected by iron strips, wooden blocks, cobble stones, steel rails, and metal grids are some of the kinds used in sluice-boxes where the ordinary run of coarse and fine gravel must be handled. For fine sand and gravel, smaller riffles of carpet, blanket,



—From Engineering and Mining Journal

Figure 8
Sluicing gravel at the Alaska fields: hand method of moving the material.

burlap, cocoa matting protected by expanded metal, corrugated rubber, sponge rubber, or riffles are used. The form of riffles and the spacing should be such as to permit large stones being slid or rolled along the bottom of the sluice. Riffles are subjected to intense wear and the surface receiving the wear should be protected by steel strips wherever possible.



—From Engineering and Mining Journal

Figure 9
Plan of flume type of sluice and riffles commonly used.

Length of Sluices:

Sluices should be long enough to disintegrate the gravel and free the gold. For loose gravel this is accomplished in 100 to 300 feet. Crude shoveling-in operations in Alaska often used only 3 to 6 boxes with a total length of 36 to 72 feet. No attempt was made to save very fine gold. Drops (vertical falls) may be installed (where topography allows) to break up cemented gravels and lessen the length of sluice. The general practice is to lengthen a sluice so long as the yield from the lower boxes, exceeds the cost of installing and operating them. The velocity of flow largely determines the minimum size of colors caught by the riffles, therefore, a greater length than is necessary to disintegrate the gravel is useless. Short sluices with drops and undercurrents are often more efficient gold-savers than long sluices without them.

Method of Cleaning-Up

The clean-up, which is usually made weekly or at 10-day intervals, is simple, although details vary more or less at different mines. The riffles are first removed by withdrawing the nails holding them to the boxes and are washed free from all adhering gold and gravel. As a general thing, except perhaps once a month or at the end of the season's work, only the upper boxes are cleaned up, since these and the dump box catch by far the greater proportion of the gold. If it is not desired to take the time and labor necessary for a careful clean-up, the gold may be concentrated without moving, but it is more often shoveled into pails or pans and carried to the upper boxes. A box that is smooth and comparatively free from knot-holes, cracks and seams, near the lower end of those to be cleaned, is then chosen, and a block of wood 2 or 3 inches high is fitted tightly into this to serve as a dam to catch the black sand and other concentrates.

Water is next turned on in just sufficient quantity to move the material slowly down the boxes and is carefully regulated to prevent too rapid movement, since the gravel and gold, on passing from a rough box into one with a smooth bottom, are likely to be flushed down too quickly, in which case they may over-ride the dam and make it necessary to carry everything back to the upper boxes. Two or three men, with wooden paddles about 3 feet long and 3 inches wide work over the concentrates as they wash down, placing the paddles on the

bottom and pushing up against the current through the concentrates. Care is taken to keep far enough down, moving from place to place, to avoid disturbing the gold, which collects at the upper end and becomes cleaner as the whole gradually works down. All rocks of any size are thrown out by hand. The water is turned off while the gold, containing considerable black sand and other imprities, is several feet above the wooden block inserted as a dam. A large flat rock is placed against one side of the box, and the enriched concentrate is brushed over against this side. A little water is then turned on, and the gold is cleaned by brushing the water against the concentrate with a stiff whisk-broom. The black sand is gradually washed away, the gold remaining behind in a comparatively clean condition. The clean-up may be helped by dividing the concentrates into two or more parts to be worked over by two or more men. In any event one man usually goes over the upper boxes with a whisk broom and carefully brushes down all gold that has remained behind This is not done if only a rough clean-up is desired, and if little time is available the concentrates as stopped by the dam, gold and all, may be removed at once from the box and cleaned by panning or otherwise.

POWER METHODS OF EXTRACTION

Some localities are known where gold occurs in gravels in amounts too small to be worked by hand at a profit. With mechanical means of handling these gravels, much more yardage can be worked so that these deposits may pay. Such machines should be small and inexpensive. They should be so constructed that they could be moved easily along a river bank. The power plant should be a small gasoline engine They should be operated by from one to three men. Such a machine should be equipped with a small pump to furnish water.

Portable machines for extraction of gold naturally are built upon the simple basic principles of equipment used in hand methods. Therefore these machines fall under the heading of mechanically operated pans, rockers and sluices.

A mechanical gold pan as shown in Figures 10 and 11 is manufactured by the Denver Equipment Company of Denver, Colorado. This machine has the oscillating motion of the hand operated pan. It has a hopper at the top with screens. Below the screens are three pans, one under the other. The top pan is a copper amalgamating pan, and

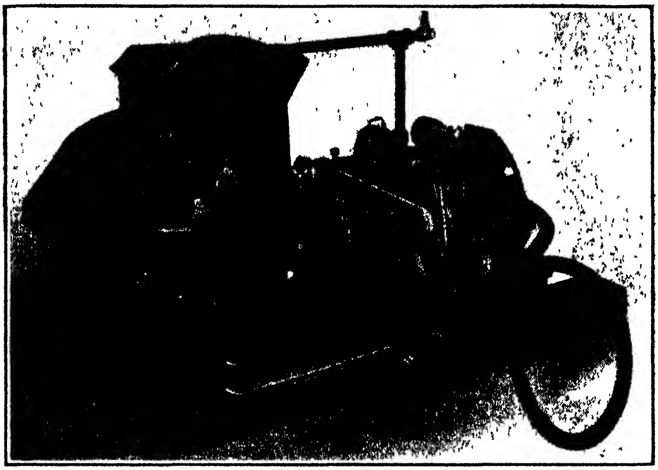


Figure 10

The Denver Mechanical Gold Pan, assembled ready for work. The hose shown at the right brings the water to the machine.

the lower two pans are of steel with a piece of rubber matting on the bottom and a heavy wire screen placed over the matting A small pump furnishes water for the operation. The machine is powered by a ¾ horsepower gasoline engine, which is said to use but 1 gallon of gasoline in ten hours. It is claimed that this machine will handle 1½ cubic yards of gravel per hour.

Mechanically Operated Sluices:

Preliminary tests are being made on a mechanically operated wide sluice at the Washington State College School of Mines. It involves the use of a trommel above the hopper which will screen out the coarse gravel. The sluice box has corrugated rubber riffles on the upper part and a sponge rubber on the lower part. An eccentric motion is given the sluice box. A small gasoline engine will furnish power for the trommel, eccentric motion, and the pump which feeds the water into the machine. Tests made so far indicate that this machine will separate fine gold that would not be caught by ordinary hand methods. The machine will be of simple design, easy to build and will be mounted on runners so that it can be dragged along so as to be near

the point of excavation and so that the oversize gravel will not hamper operations. *Gravel will be shoveled into the hopper by hand.* Drawings and a description of this machine will be furnished on request after this machine has been developed.

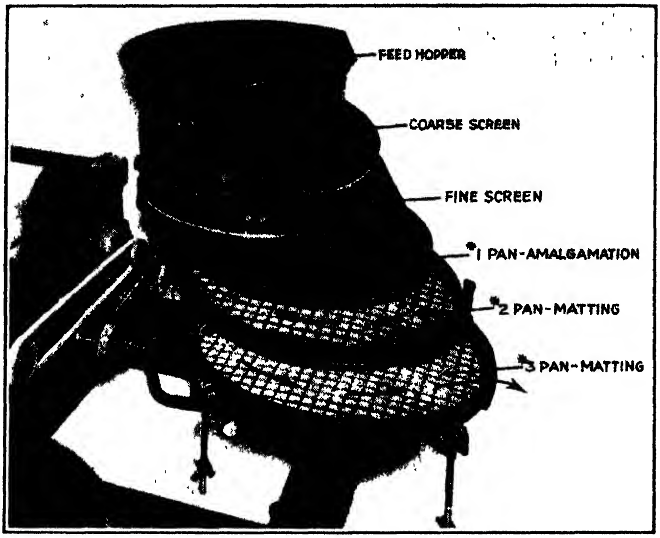


Figure 11

The Denver Mechanical Gold Pan opened up with the pans pulled out showing construction

A machine somewhat similar to the one described above is on the market. It is the G-B Portable Placer Machine, manufactured by the Mine and Smelter Supply Company, of Denver, Colorado. This machine is designed for deposits where there is a scarcity of water for placer mining. It consists of a tank, holding about 42 gallons of water, upon which is built a feed hopper, launders, mechanically agitated riffles, and a drag classifier which dewaters the tailings. The riffle pans are made of copper and can be amalgamated The water is used over and over. A ¾ horsepower gasoline engine operates the machine. The machine can be placed on the rear seat of an automobile. The G-B Portable Placer Machine is shown in Figure 12.

METHODS OF CATCHING FINE GOLD

Methods of catching fine gold may be divided into Mechanical and Chemical methods. Mechanical methods include the use of apparatus such as undercurrents, canvas tables and some of the power placer mining machines. Chemical methods include amalgamation and flotation.

Mechanical Methods:

It may be well to mention a few of the basic principles to consider in the saving of fine gold by mechanical means. Among these principles are sizing or screening of the material, velocity of the water and the surfaces used in catching the gold.

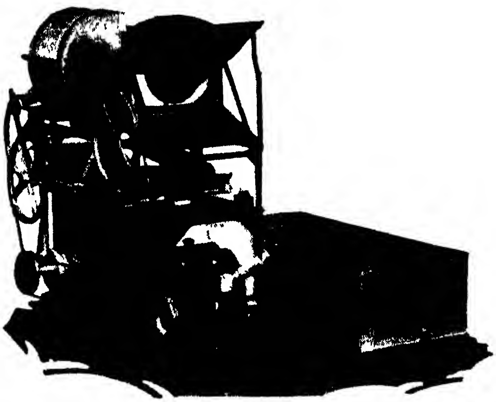


Figure 12

The G B Portable Placer Machine This machine is designed for localities where water is not plentiful

Screening: It is important to screen out the coarse material It requires a much greater volume and a very much greater velocity of water to carry coarse material than to carry fine sands Water at this great velocity would carry the fine gold and not allow it to settle Coarse material might injure the surfaces for catching fine gold. It has been found that material passing through a 10-mesh screen is suitable to use in most of the processes for catching fine gold.

The separation of the coarse gravel may be accomplished by the use of grizzlies, screens or trommels Grizzlies consist of parallel bars

or rails separated by varying fixed distances, usually set on an incline. When gravel or other material made up of pieces of various sizes is dumped upon a grizzly, much of the finer material or undersize will fall between the rails and the coarser material, or oversize, will slide over the rails. Screens may be of woven wire, or may be a steel plate with holes punched in it. The mesh of wire screens is designated by the number of openings per lineal inch. Thus 40-mesh screen has 40 openings per lineal inch, or a square inch of 40-mesh screen would have 40 x 40 or 1600 openings in it.

A trommel is a revolving screen. It consists of a cylinder open at both ends with one or more screens around it. A trommel revolves upon an axis and usually slopes so that the oversize of the material fed into the upper end will roll out of the lower end. With material like gravel where it is necessary to screen out fine material, it is often desirable to separate the coarse material first in order to protect the finer screens. This may be accomplished by having a steel plate with large openings on the inside of the trommel. Outside of this screen is a finer one which receives the undersize of the coarser one. Trommels for screening gold bearing gravels often have in them a pipe with holes in it for spraying water on the gravel. This water and the rubbing of the pebbles as the trommel revolves breaks up the clay, loosens the fine sand and gold and washes it through the screens. The pebbles assist in scouring up the gold and thus make it easier to amalgamate if desirable.

Gravels may be screened by hand through a sloping wire screen, but unless water was sprayed upon the screen a considerable amount of gold would stick to the pebbles and be lost.

Velocity of the Water: It was stated above that the greater the velocity of the water the larger or heavier the material it would carry. If water with a velocity great enough to carry sand and gravel is slowed up, some of the coarser and heavier material will settle out. If one of two particles of the same size is heavier than the other, the heavier one would settle in running water quicker than the lighter one. Thus gold being about five times as heavy as ordinary rock will settle out much faster than sand. The gold found in the sands of the large rivers is usually very fine or in thin flakes and easily carried by swift currents of water. To catch this gold it is necessary to get it into a

stream of water that will carry it and then slow up the water and let it settle out on a surface that will hold it. The river sands usually contain black sands which are quite heavy and will ordinarily settle out with the fine gold. This often packs in the riffles or surface for holding the gold and the gold then slides over the black sand and is lost. It is believed that a vibrating motion of a sluice or table for fine gold will keep the black sand in suspension and allow the gold to settle. This principle is utilized in the machine being developed at the School of Mines at Washington State College. This machine is described above

Various materials have been used for catching fine gold. Among there are rubber matting used in the Denver Mechanical Gold Pan described above; corrugated rubber and sponge rubber used on the W. S. C. machine; canvas, burlap, carpets, blankets, etc. Screens are sometimes laid on top of this material.

Undercurrents and canvas tables, as mentioned above, are among the simple devices with no moving parts using mechanical means of catching gold These are described below

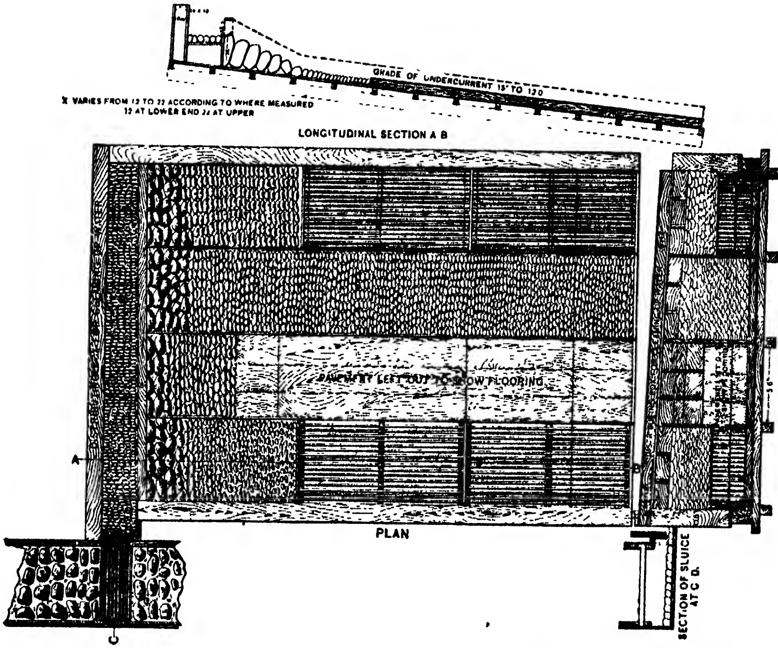
Undercurrents:

In order to relieve the sluices of the finer material, and thereby aid in saving the gold, undercurrents are introduced into the sluice line These may be described as broad sluices set on a heavy grade at the side of and below the main sluice. (See Figure 13.)

Where a drop off can be made in the main line, parallel steel or iron bars, 1 by 4 inches, with intervals of 1 inch between them, and 10 to 20 in number, according to the size of the undercurrent, are placed edgewise across the sluice A set of such bars is called a "grizzly." It is set 1 inch below the sluice pavement which is raised as it wears down. If too low, the grizzly clogs with gravel

The coarse material passes over the grizzly, and if the topography permits, is dropped and picked up again in sluices at a lower level

The finer gravel drops through the bars into a box about 20 inches deep, lined with blocks and set at right angles to the main line This box carries the material to the chute at the upper end of the undercurrent.



—From Bowie "Hydraulic Mining"

Figure 13
North Bloomfield Undercurrent.

This chute is lined with cobbles and provided with "dividers" of wood to evenly distribute the material over the surface of the undercurrent. It has 2 or 3 per cent grade and gradually narrows toward the lower end The undercurrent proper is a shallow wooden box, 20 to 50 feet wide, and 40 to 50 feet long, with sides about 16 inches high. It should have, if possible, 8 to 10 times the width of the main sluice. The bottom is made of 1½ inch plank tongued and grooved, and set on a grade of 8 to 10 feet drop to 100 feet, according to the smoothness of the riffles employed. It is paved with cobbles, wooden rails shod with strap iron, or small wooden blocks. With the smooth rails a grade of 12 inches in 12 feet is sufficient; but with blocks the grade should be increased to 14 inches in 12 feet, and with cobbles to 16 inches in 12 feet.

The gravel escaping from the undercurrent is led back to the main sluice.

The chief cost of maintenance is occasioned, not by the undercurrent itself, but by the repairs on the main sluice and grizzly, caused by the introduction of the latter into the sluice line. The running expense of a wide undercurrent is no more than that of a narrow one, excepting in the slight matter of pavement and cleaning-up.

An interesting account of the use of undercurrents to catch fine gold in the Snake River is found in Transactions of American Institute of Mining Engineers, Volume XVIII, 1889, pages 597 to 609. The sands worked were bars in the river Ditches carried the water and gravel to sluices with "grizzlies" of perforated iron plates. The finer material was carried to undercurrents covered with burlap weighing 7 ounces to the yard. The length and grade of the sluices and undercurrent varied with the conditions present. In the clean-up the burlap was taken out of a section and washed in a tank of water.

Canvas Tables:

Canvas tables are inclined rectangular tables covered with canvas (cotton duck) Figure 14 shows a canvas table The table has a slope of from ½ inch to 1 inch per foot. It is about 8 feet wide and 16 feet long. The table is divided into four longitudinal sections by strips of wood, and the feed is made so that the flow can be cut off any section

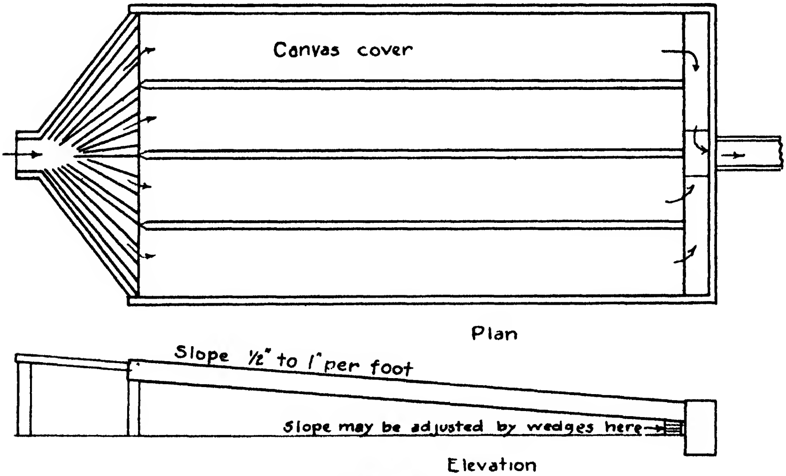
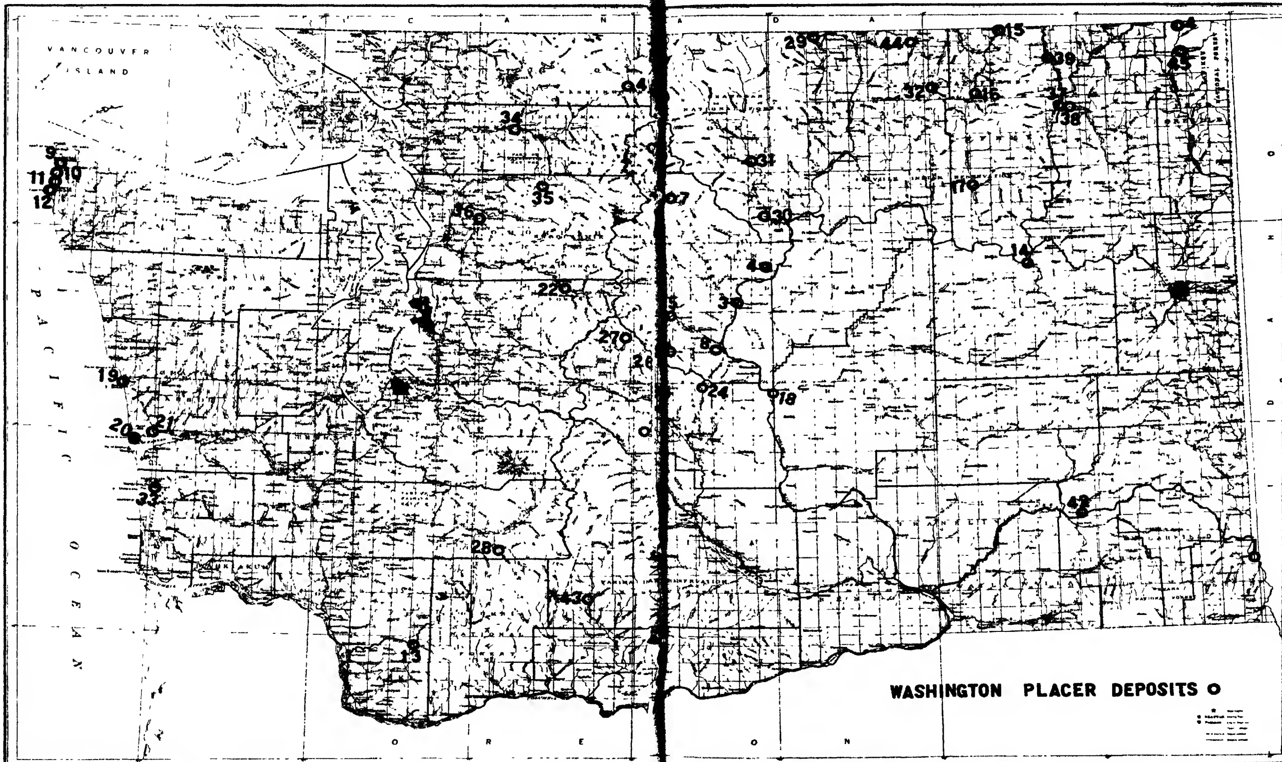


Figure 14

Canvas Table.


WASHINGTON PLACER DEPOSITS
VANCOUVER ISLAND
PACIFIC OCEAN
CANADA
OREGON
IDAHO

for clean-up, allowing the other sections to carry the sands. The fine sand, to which the clean water is added if necessary, is evenly distributed across the upper margin as it flows down. The sizing action of the film of water operates more effectively than with a smooth bottom. When the meshes have become pretty well filled with black sands and gold the flow of sand is stopped and the remaining sand washed off with clear water, and finally the concentrate either washed or broomed off.

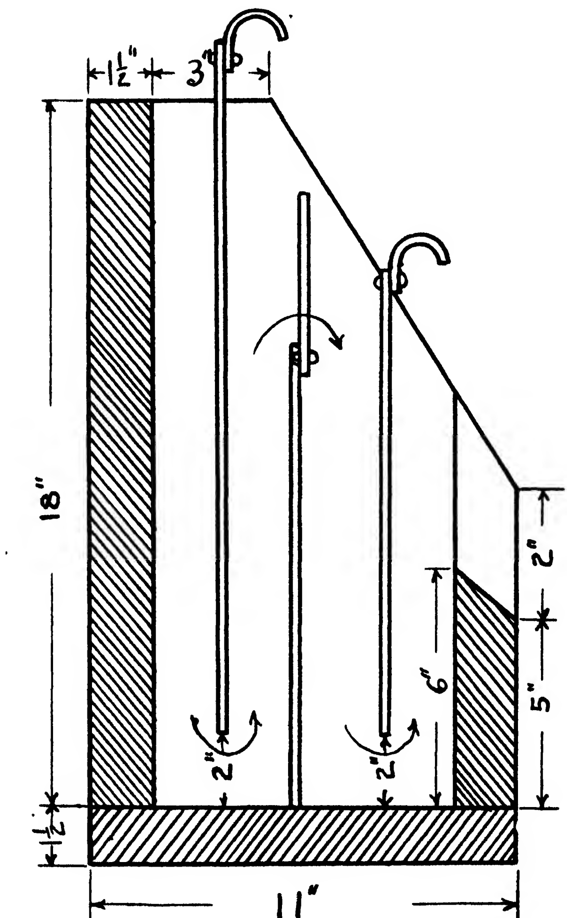
As the warp of the canvas always projects higher than the woof a piece of duck will offer more resistance by placing the warp across the table, than when down the table. On the other hand a coarser duck run lengthwise may have the same effect as finer duck laid acrosswise. Various grades of cotton duck are used ranging from No. 4 to No. 8. Each side of the latter has a life of about 5 months when washed off with a wide, flat, broom-shaped jet, which is much more effective than a corn broom, and, moreover, the use of a broom halves the life of the canvas. The canvas is usually slipped up a little every four or six weeks to relieve it from wear due to the joints on the board table beneath, and when worn out on one side, so that it ceases to catch well it is turned over. When a new canvas is put on, the old one is burned, the ashes being worked up for gold. Canvas tables operate most efficiently on fine sands which would pass 60 to 100 mesh screens.

Sponge rubber could be used instead of canvas on these tables and it is likely that the gold recovery would be greater. To make a clean-up the sponge rubber cover would have to be removed and washed in a tub of water.

"Rusty" Gold:

"Rusty" gold is gold that has a surface coating of iron oxide, grease, or a film of antimony or arsenic. "Rusty" gold may be difficult to separate from black sands by amalgamation because the mercury will not wet the gold. For small clean-ups the black sands and "rusty" gold may be put in a porcelain dish and barely covered with water. A few drops of concentrated nitric acid added to the mixture will probably clean the gold so that mercury will wet it and separate it from the black sands. For larger amounts of concentrates a "clean-up" barrel is used if the gold is "rusty." A clean-up barrel is a cylindri-

cal steel drum mounted upon an axis so that it can be revolved. The barrel has a small opening which can be tightly closed with bolts. It should be tight so as to hold mercury. The black sand with the "rusty" gold and some mercury are put into the barrel. Coarse gravel is added and the opening closed, and the barrel is revolved The grinding action of the pebbles will scour the gold, and the mercury will amalgamate it.



—From Richards "Ore Dressing."

Figure 15
Cross section of Black Hills Trap.

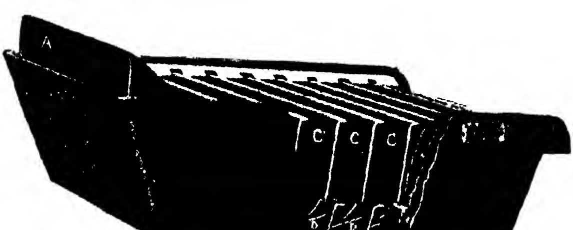
AMALGAMATION

Amalgamation is the property of mercury which enables it to form alloys with gold and silver.

Amalgamation Apparatus: There are numerous devices to recover gold by amalgamation. Three forms of amalgamation apparatus will be described here: The Black Hills mercury trap, the Pierce Amalgamator, and the Gibson Impact Amalgamator. These amalgamating devices operate most efficiently on material passing at least a 10-mesh screen.

The Black Hills Mercury Trap: The Black Hills trap, shown in Figure 15 consists of two adjustable gates and one dam, all of wrought iron and sliding in grooves in a rectangular wooden box. The gold bearing sands enter the box at the feed end, pass down under the first gate, up over the overflow which is considerably below the level of the feed. The trap is 48 inches long, 14 inches wide, and 48 inches deep The gates are all 3 inches above the bottom The dams are 1½ 3 and 4 inches respectively below the top Mercury is poured in the trap so that the lower part of the plates are slightly covered The plates can be raised or lowered so that if the trap overflows at the back the plate can be raised slightly In cleaning Black Hill traps, the gaters and dam are all taken out The amalgam is removed and treated This process will be described later

Pierce Amalgamator: The Pierce Amalgamator consists of numerous L-shaped copper riffles (C) (Fig. 16), which are treated with quicksilver. These are so arranged that the water carrying the sand enters at (A) and sweeps all particles repeatedly against the amal-



—From "The Mine and Smelter Supply Company" catalog.

Figure 16
Pierce Amalgamator.

gamated surfaces (C). The L-shaped bottoms of the riffles (D) also contain quicksilver into which "rusty" gold iwll sink by gravity.

Gibson Impact Amalgamator: This machine is manufactured by W. W. Gibson, San Francisco, California. This amalgamator consists of a tray with a rubber bottom to which baffles are attached. These baffles hold up 5 or more plates silvered on both sides. The plates stand on edge and extend the full length of the amalgamator. They can be removed easily for a clean-up. There are riffles in the amalgamator bottom at right angles to the plates, which gradually decrease in height from the intake to the discharge end. A lid is bolted down over the tray. The Gibson Impact Amalgamator is operated with a head-motion and is generally operated on the decks of concentrating tables, but a head-motion and frame can be purchased This machine is shown in Figure 17.

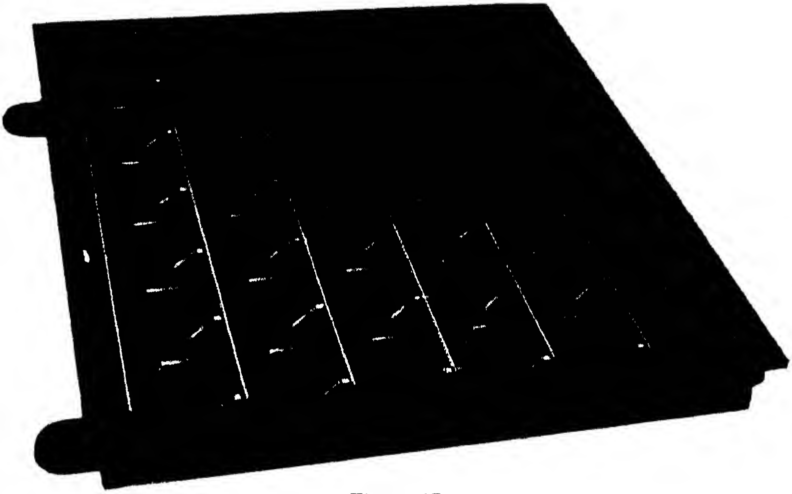


Figure 17

The Gibson Impact Amalgamator The upright plates are of copper and are silver-plated They are held in place by rubber baffles.

CARE OF AMALGAMATION PLATES

Amalgamation plates are of copper and are usually silver plated. The amount of silver varies from 1 or 2 to 5 ounces per square foot of plate. If the copper is not silver plated it is more difficult to keep

the plates in good condition. To prepare the copper plates for amalgamation they may be washed with caustic soda and scoured with sand to remove all traces of grease. A small amount of mercury is then sprinkled on the plate and rubbed on thoroughly. A whisk broom is often used to distribute the mercury over the plate. If gold or silver amalgam is available it should be rubbed on the plate as it will help to catch gold If too much mercury is put on the plates there will be a loss of both mercury and gold. If there is not enough mercury on the plates the coarse gold may be caught but the fine gold will escape. The mercury is best sprinkled on with a small iron bottle or pipe with cloth, such as bed-ticking tied over the top. This cloth should be kept dry.

To clean up the plates, a small amount of mercury is sprinkled on to soften the amalgam. This is rubbed lightly, after which the amalgam is scraped up from the lower end with a rubber or hard-wood scraper Near the head-end scraping is done with an amalgam knife or chisel, but care must be taken not to groove the plate. After the amalgam is removed fresh mercury is sprinkled on the plates.

Care of Mercury:

Mercury sometimes becomes contaminated with grease or thin films of sulphates and other chemicals. It gathers in small globules which will not unite nor amalgamate gold, and the mercury is said to be "sick." Squeezing the mercury through cloth or chamois will not remove these films. It should be covered with a weak acid solution, or lye or metallic sodium, or even be retorted before using again

Cleaning Amalgam:

The amalgam before cleaning, is mixed with more or less sand, and other materials Amalgam is softened with an excess of mercury and stirred in buckets or ground in a mortar to bring the base material to the top for removal. The excess mercury is removed from the cleaned amalgam by squeezing through chamois skin, or drill, or other strong cotton cloth. The amalgam may be sold to an assayer or may be retorted.

Retorting Amalgam:

The cleaned amalgam is broken and packed loosely into a pot retort which is a kind of still, coated inside with clay, chalk, or paper.

The retort should not be more than three-quarters full. The cover is provided with an asbestos gasket or luted with clay to assure a tight fit and keyed down. The retort is then placed on its stand and heated by wood, coal or gasoline. The heat should be raised very gradually, as volatization of the mercury should not start for about one hour. The mercury fumes are condensed in an iron pipe leading from the top of the retort and fitted with a condenser through which water runs continuously. The mercury is recovered in a vessel containing water If no condenser is provided, the pipe should be covered with gunny sacking kept thoroughly wet The retort should be kept at dark-red heat until nearly the end, when the heat is raised to cherry red. This heat is maintained for 15 minutes or so after the last of the mercury has been driven off. The pipe is usually tapped with a hammer to determine whether volatization is complete

Precautions: The retort is allowed to cool gradually and should not be opened until cold. **Care must be taken to do all retorting in a well-ventilated place, with the outlet of the retort kept outdoors, for mercury fumes are very poisonous.** The lower end of the retort pipe should not be under water, for a fall in the temperature might create a vacuum, thus drawing the water into the retort and causing an explosion It is safer to place a piece of sacking over the end and keep it soaking wet.

The small balls of amalgam obtained by the lone miner are often placed on a shovel and held over a fire to drive off the mercury **This should only be done outdoors, and the miner should keep away from the fumes.**

FLOTATION

Flotation is based upon the principle that most metals and metallic minerals, when mixed with water and a small amount of certain reagents, collect these reagents on their surface and are floated by bubbles attaching themselves A frothing agent causes a foam which floats on the top of the liquid and catches the metals or minerals According to A W Fahrenwald in the Mining Journal, January 30, 1933, "The flour gold in river bar sands, only a small percentage of which can be caught by dredging, is readily recovered by flotation The gravel is screened on a 14 to 20 mesh screen to remove coarse sand, pebbles and boulders. The product passing through the screen

can then be floated direct. The concentrate produced usually does not weigh more than one-hundredth of the original and assays $100 to $1000 a ton. The gold floated from black sand concentrate is nearly pure gold, only a little of the sand floating." This process would require the handling of the gravel in large amounts.

THE FOLLOWING POINTS WERE EMPHASIZED AT THE PLACER MINING SCHOOLS WE PARTICIPATED IN DURING THE SUMMER OF 1932.

1. Don't start out on a prospecting trip without the proper amount of equipment. Have food and clothing for at least 30 days. The game laws apply to prospectors as well as to the other people.
2. Don't expect to have an easy time prospecting. Placer mining is hard work and you will probably meet with many disappointments
3. Don't work on privately owned land or on anyone's claim without permission. You have no right to do so.
4. Don't work on state-owned lands of the State of Washington without a lease from the Commissioner of Public Lands, Olympia. The lands below high-water mark on navigable rivers such as the Snake and Columbia are owned by the State.
5. Don't expect as a "greenhorn" to start placer mining and make a living from the beginning; you can do better to start with an experienced placer miner and learn how and where to mine placer gold.
6. Don't expect to pick up gold nuggets on the river bars; it is not as easy as that.
7. Don't get discouraged if you do not find gold in paying quantities the first day you start.
8. Don't expect to make a good living with only a pan when working placer ground carrying less than $5.00 a cubic yard in gold. A good panner can hardly pan a cubic yard of gravel a day under the best of conditions.
9. Don't expect to make a good living with only a rocker when working gravel carrying less than $1.00 per cubic yard in gold.
10. Don't be discouraged if you do not make over 25 or 50 cents per day as a start. That is much better than being unemployed in the city.

PLACER MINING DISTRICTS OF WASHINGTON AND OREGON

The placer deposits shown on the accompanying maps are localities that have been reported to carry placer gold. Some of these deposits may have been worked out and some may have carried only colors of gold. Therefore the author does not guarantee that all of these deposits carry gold now, nor does he wish to give the impression that the list is complete. It is hoped that the maps will help the seeker of placer gold to find a place to work. The placer gold found in the Columbia, Pend Oreille and Snake rivers is found in sand bars The high waters of spring bring down fine gold and deposit it so a crop of gold may be taken out every year.

Placer Districts of Washington (See map of Washington pp 30-31)

Asotin County

1. Asotin (Snake River bars) Clarkston

Chelan County

2 Bridge Creek
3. Entiat
4. Lakeside
5 Leavenworth
6 Peshastin (Blewitt)
7. Railroad Creek
8. Wenatchee

Clallam County

9 Shishi Beach (Platinum and gold).
10. Ozette Beach (Platinum and gold)
11. Yellow Banks (Platinum and gold).
12. Sunset Creek (Platinum and gold).

Clark County

13. South Fork Lewis River

Douglas County

3. Columbia River bars

Ferry County

24 Naneum Creek
25. Manatash Creek
26 North Fork Teanaway River
27. CleElum River

Lewis County

28 McCoy Creek

Lincoln County

14. Columbia River bars

Okanogan County

29 Similkameen River (Platinum and gold)
30. Squaw Creek (Methow)
31. Twisp
32 Wauconda
44. Mary Ann Creek

Pacific County

33 Fort Canby

Pend Oreille County

45. Sullivan Creek
46. Pend Oreille River Russian Creek

Skagit County

34. Skagit River

Snohomish County

35. Darrington

14. Columbia River
15. Danville
16. Republic (Eureka)
17. Bridge Creek

Grant County

18. Trinidad

Grays Harbor County

19. Moclips River
20. Point Brown
21. Cow Point

King County

22. Money Creek

Kittitas County

23. Swauk (Liberty)

36. Granite Falls

Stevens County

37. Kettle Falls (Columbia River bars)
38. Meyers Falls (Columbia River bars)
39. Orient

Whatcom County

40. Slate Creek (Barron)
41. Ruby Creek

Whitman County

42. Riparia (Snake River)

Yakima County

43. Surveyors Creek

Placer Districts of Oregon (See map of Oregon)

Baker County

1 Buck Gulch
2. Conner Creek
3 Pocahontas
4. Rye Valley
5. Willow Creek
6. Chisholm Creek (Sisley Creek)
7. Clark Creek (Burnt River)
8. Muddy Creek
9. Sumpter
10. Greenhorn Mountains

Coos County

11. Eden
12. Myrtle Point (Johnson)
13. Randolph
14. China Flat (S. Fork Coquille River)

Curry County

15 Gold Beach
16. Chetco
17. Lower Rouge (Mile Creek)
18. Rusty Butte
19. Sixes River

Douglas County

20. Crackerjack (Cow Creek)
21. Dothan

Grant County

25 Alamo
26. Canyon
27. Crane Creek
47. Murderers Creek

Jackson County

28. Applegate
29. Ashland
30. Gold Hill (Foots Creek, Galls Creek, Sardine Creek)
31. Jacksonville
32. Pleasant Valley(Evans Creek)
33 Prospect

Josephine County

34. Althouse
35. Applegate
36. Greenbank (Upper Grave Creek)
37. Jumpoff Joe
38. Kerby
39. Louse Creek (Granite Hill)
40. Lower Grave Creek
41 Wolf Hill
42. Waldo

Malheur County

43. Humboldt

22. Nugget (Myrtle Creek)
23. Olalla
24. Starvout (Green Mountain)

44. Malheur (Mormon Basin)

Union County

45. Camp Carson
46. Limber Creek

MINING LAWS

Character of Mining Laws

These laws define the status of the prospector for mineral deposits, establish his method of procedure, protect him in possession while searching for mines, and give him assurance of title when all required conditions have been fulfilled and valuable minerals discovered.

Importance of an Understanding of Mining Laws

There is always a prescribed course of procedure to be followed in acquiring and perpetuating such title as is granted by the laws, both while a property is in exploratory stages and after ores have been discovered; and without strict compliance with these statutory provisions there is danger of losing the mines after they have been proven to be of value.

Mining Law of 1872

On May 10, 1872, Congress passed a law entitled "An act to promote the development of the mining resource of the United States" This, with a few additions and amendments, is the law under which mining rights are acquired today, and in accordance with its provisions the vast majority of mining claims in the territory to which it applies have been located.

Text of the Statute

Title XXXII, Chapter 6. Revised Statute. 2319. Who May Locate: "All valuable mineral deposits in lands belonging to the United States, both surveyed and unsurveyed are hereby declared to be free and open to exploration and purchase, by citizens of the United States and those who have declared their intention to become such, under regulations prescribed by law."

2321. Proof of Citizenship, under this chapter, may consist, in the case of an individual, of his own affadavit thereof; in the case of an association of persons unincorporated, of the affadavit of their authorized agent, made on his knowledge or upon information and belief, and in the case of a corporation organized under the laws of

the United States, or of any State or Territory thereof, by the filing of a certified copy of their charter or certificate of incorporation.

2329. Lands Open for Staking Placer Claims. Placers and other forms of deposit not in place may be entered and patented. Claims usually called "placers," including all forms of deposit, excepting veins of quartz, or other rock in place, shall be subject to entry and patent, under like circumstances and conditions, as are provided for vein and lode claims; but where the lands have been previously surveyed by the United States, the entry in its exterior limits shall conform to the legal subdivisions of the public lands.

Indian, Military, and Forest Reservations: No valid locations can be made within an Indian reservation. Nor can a valid location be made upon a military reservation unless the latter has been abandoned and restored to the public domain. The same is true of tracts of land reserved for public parks such as the Yellowstone National Park.

The title to minerals under the sea and navigable rivers is in the sovereign In the United States this means the State adjacent to the navigable water.

2330. Subdivision of Claims. Group entries. Maximum extent of placers. Legal subdivision of 40-acres may be subdivided into 10-acre tracts; and two or more persons, or associations of persons, having contiguous claims of any size, although such claims may be less than 10 acres each, may make joint entry thereof; but no location of a placer claim, made after July 9, 1870, shall exceed 160 acres for any person or association of persons, which location shall conform to the United States Surveys; and nothing contained in this section shall defeat any bona fide pre-emption or homestead claim upon agricultural lands, or authorize the sale of the improvements of any bona fide settler to any purchaser.

2331. Placer Locations Must Conform to Public Surveys. Where placer claims are upon surveyed lands, and conform to legal subdivisions, no further survey or plat shall be required, and all placer mining claims located after May 10, 1872, shall conform as nearly as practicable with the United States system of public land surveys, and no such location shall include more than 20 acres for each individual

claimant; but where placer claims cannot be conformed to legal subdivisions, survey and plat shall be made as on unsurveyed lands.

Placer Claims. Discovery Necessary. As in the case of lode claims, a discovery of valuable mineral in place is necessary before location of a placer claim. Proceedings to obtain patents for placer claims, including all forms of mineral deposits, excepting veins of quartz or rock in place, are similar to those prescribed for obtaining patents for vein or lode claims, but where a placer claim shall be upon surveyed lands, and conform to legal subdivisions no further survey or plat will be needed. The price fixed by law for placer claims is $2.50 per acre or fractional part of an acre.

Size and Shape

According to the United States law no location shall exceed more than 20 acres for each individual locator. It is the policy of the government to have entries, whether they be of agricultural or mineral lands in compact form. No shoestring claims should ever receive the sanction of this department (Department of the Interior). If the land be unsurveyed, the location as reasonably as practicable, must be rectangular in form, with east and west, and north and south boundary lines, and otherwise approximating conformity to the public survey system within the limits of practicability If the boundaries of other claims interfere with making the location conform to legal subdivisions and rectangular shape, the locator may conform his boundaries to those of the surrounding claims. Where the mineral ground is confined within a narrow canyon the location need not conform to the subdivisions. The Department of the Interior has made a like ruling in cases involving "gulch" claims.

Number of Claims

The Supreme Court of New Mexico has held that one person may locate as many placer claims as he desires.

Discovery

An appropriate discovery of mineral is necessary to the lawful location of a placer mining claim.

Location by an Association

The United States law permits two or more persons up to the number of eight to locate an association claim, 20 acres to each person. A person cannot by the use of names of his friends, relatives, or employees as dummies, locate for his own benefit a greater area of placer ground than is allowed by law.

Placer Mining Laws of the State of Washington

Placers

Section 10. The discoverer of placers or other forms of deposit subject to location and appropriation under mining laws applicable to placers shall locate his claim in the following manner:

First. He must immediately post in a conspicuous place at the point of discovery thereon a notice or certificate of location thereof, containing (a) the name of the claim; (b) the name of the locator or locators; (c) the date of the discovery and posting of the notice hereinbefore provided for, which shall be considered as the date of the location; (d) a description of the claim by reference to legal subdivisions of sections, if the location is made in conformity with the public surveys, otherwise a description with reference to some natural object or permanent monument as will identify the claim, and where such claim is located by legal subdivisions of the public surveys, such location shall, notwithstanding that fact, be marked by the locator upon the ground the same as the other locations.

Second. Within thirty (30) days from the date of such discovery, he must record such notice or certificate of location in the office of the auditor of the county in which such discovery is made, and so distinctly mark his location on the ground that its boundaries may be readily traced.

Third. Within sixty (60) days from the date of discovery, the discoverer shall perform labor upon such location or claim in developing the same to an amount which shall be equivalent in the aggregate to at least ten (10) dollars' worth of such labor for each twenty acres, or fractional part thereof contained in such location or claim—"provided, however, that nothing in this subdivision shall be held to apply on lands located under the laws of the United States as placer claims

for the purpose of the development of petroleum and natural gas and other natural oil products."

Fourth. Such locator shall, upon the performance of such labor, file with the auditor of the county an affidavit showing such performance, and generally the nature and kind of work so done.

Evidence

Section 11. The affidavit provided for in the last section, and the aforesaid placer notice or certificate of location, when filed for record shall be prima facie evidence of the facts therein recited A copy of such certificate, notice or affidavit certified by the county auditor shall be admitted in evidence in all actions or proceedings with the same effect as the original, and the provisions of section six (6) and seven (7) of this act shall apply to placer claims as well as lode claims.

Future Locations

Section 12. All locations of quartz or placer formations of deposits hereafter made shall conform to the requirements of this act in so far as the same are respectively applicable thereto.

Mining Districts

Section 13. Any mining district organized in the State of Washington in accordance with the laws of the United States, shall have power to make rules and regulations for such mining district, providing such rules and regulations do not conflict with the laws of the State of Washington or of the United States.

Road Building

Section 14 Any mining district shall have the power to make road building to mining claims within such a district applicable as assessment work, or improvement upon such claims: **Provided,** That rules pertaining to such road building shall be made only at a public meeting of the miners of such district regularly called by the mining recorder of such district: **Provided further,** That such meeting shall be attended by at least twelve property holders of such district, and that no such rule can be made without the assent of the majority of the property holders of such district, who are present at such meeting.

Such meeting to designate where, when and how such road work shall be done, and shall designate some one of their number who shall superintend such road building or construction, and who shall receipt for such labor to the performer thereof, such receipts to be filed with the county auditor of the county in which such work is performed by the holder or holders of such receipts, and shall be received as prima facie evidence of labor performed as annual assessment work upon such claims or claims, as may be designated by an affidavit or oath of labor as provided for in section six (6) of this act: Provided, that nothing in this act can be construed as being mandatory upon any owner or holder of mining property to perform labor upon any such road.

Relating to Monuments and Notices on Mining Claims:

Sec. 1. Any person who shall wilfully and maliciously deface, remove, injure, or destroy any location stake, side post, corner post, landmark or monument, or any other land boundary monument, the same having been erected or implanted for the purpose of designating the location, boundary or name of any mining claim, lode or vein of mineral, or for posting the name of the discoverer, locator or owner or date of discovery thereon; or any person who shall so deface, obliterate, remove or destroy any notice having been placed or posted upon any mining claim for the purpose of marking or identifying the same, shall be deemed guilty of a misdemeanor, and upon conviction thereof shall be punished by a fine of not less than one hundred dollars ($100) nor more than five hundred dollars ($500), or by imprisonment in the county jail not exceeding one year; **provided, however**, that the provisions of this act shall not apply to abandoned mining claims.

Lands Owned by the State of Washington:

According to the Constitution of the State of Washington: "The State of Washington asserts its ownership to the beds and shores of all navigable waters in the state up to and including the line of ordinary high tide in waters where the tide ebbs and flows, and up to and including the line of ordinary high water within the banks of all navigable rivers and lakes."

"The use of the water of this state for irrigation, mining and manufacturing purposes, shall be deemed a public use."

The Constitution of the State of Washington does not assert ownership to the beds and shores of the non-navigable lakes or streams.

A letter from the office of the Attorney General of the State of Washington states: "We are of the opinion that it can be announced as a fixed principle of law in this State that the beds and shores of non-navigable lakes in this state belong to and title thereto is vested in the abutting owner whether the same may be meandered or not, and that the navigability or non-navigability of a lake or stream is a question of fact to be determined upon inquiry and that in determining such fact our Supreme Court follows the rule . . . . . "First, that the question as to whether or not a body of water is navigable or non-navigable is a question of fact, and is to be determined by inquiry whether it is used, or is susceptible for use, in its natural and ordinary condition, as a highway for commerce, over which trade and travel are or may be conducted in the customary modes of trade and travel on water"

Mining Leases:

The Commissioner of Public Lands of the State of Washington, Olympia, Wash, is hereby authorized to execute leases and contracts for the mining of gold, silver, copper, lead, cinnabar or other valuable minerals, except coal, from any land now belonging to the State or from any lands to which the State may hereafter acquire title, subject to the conditions hereinafter provided.

Any citizen of the United States finding precious minerals upon any land belonging to the State of Washington may apply to the Commissioner of Public Lands for a lease of any amount not to exceed eighty acres for prospecting purposes, provided that said applicant has posted up location notice and set corner post and marked boundary lines as is required by the mining laws of the State of Washington. **Provided,** any person, persons, or corporations to whom a lease or contract has been issued prior to the passing of this act may, by applying to the Commissioner of Public Lands, have the boundaries of their mineral claims or lots changed to conform to the section lines as surveyed by the U. S. surveyors: **Provided,** the changing of boundaries does not infringe on the rights of any other lease

holder or assignee, and shall pay a fee according to the mineral area which they may obtain.

Necessary Timber Privileges:

The lessee may cut and use the timber found upon said premises for fuel and construction of buildings, required in the operation of any mine or mines on the premises; also the timber necessary for drains, tramways and supports for such mine or mines, and for no other purpose.

EXTRACTS FROM THE MINING LAWS OF OREGON

Chinamen Not to Hold Real Estate or Work Mining Claims

Section 8. No Chinaman, not a resident of the State at the adoption of this consitution, shall ever hold any real estate or mining claim, or work any mining claim therein.

The legislative assembly shall provide by law in the most effectual manner for carrying out the above provision.

Defective Location Notice—How Cured

If at any time the locator of any mining claim heretofore or hereafter located, or his assigns, shall apprehend that the original notice of location of said mining claim was defective, erroneous, or that the requirements of the law had not been complied with before the filing of the said notice, such locator, or his asigns, may post and file for record in the manner now provided by law, an amended notice of the said location which shall relate back to the date of the original location, provided, that the posting and filing of such an amended notice of location shall not interfere with the existing rights of others at the time of posting such amended notice of location.

Mining Claims are Real Estate

Section 3978. All mining claims, whether quartz or placer, shall be real estate, and the owner of the possessory right thereto shall have a legal estate therein within the meaning of section 326

Taxation, Claim Exempt From, Prior to Patent

Section 3980. Prior to the obtaining of patent from the general government of the United States to such claim, the same shall be

exempt from taxation, except as to improvements, machinery, and buildings thereon.

Conveyances, Subject to Provisions Relating to Other Real Property

Section 3987. All conveyances of mining claims, or of interests therein, either quartz or placer, shall be subject to the provisions governing transfers and mortgages of other realty as to execution, recordation, foreclosure, execution sale, and redemption thereunder, but such redemption by the judgment debtor must take place within sixty days from date of confirmation, or such right is lost.

Ditches and Mining Flumes Real Property—Abandonment of

Section 3983. Ditches and mining flumes, permanently affixed to the soil, are hereby declared to be real estate: Provided, that whenever any person, company, or corporation, being the owner of any such ditch, flume, and water right appurtenant thereto, shall cease to operate or exercise ownership over said ditch, flume, or water right, for a period of five years, and every person, company, or corporation who shall remove from this State with the intent or purpose to change his or its residence, and shall remain absent one year without using or exercising ownership over such ditch, flume, or water right, shall be deemed to have lost all title, claim and interest therein.

Grub Stakiug Contracts Must Be in Writing, Requirements of

Section 3985. All contracts of mining copartnership, commonly known as "grub staking," shall be in writing, and filed for record with the recorder of conveyances of the county wherein locations thereunder are made Such contracts must contain, first, the names of the parties thereto, and second, the duration thereof; otherwise, such contracts shall be null and void.

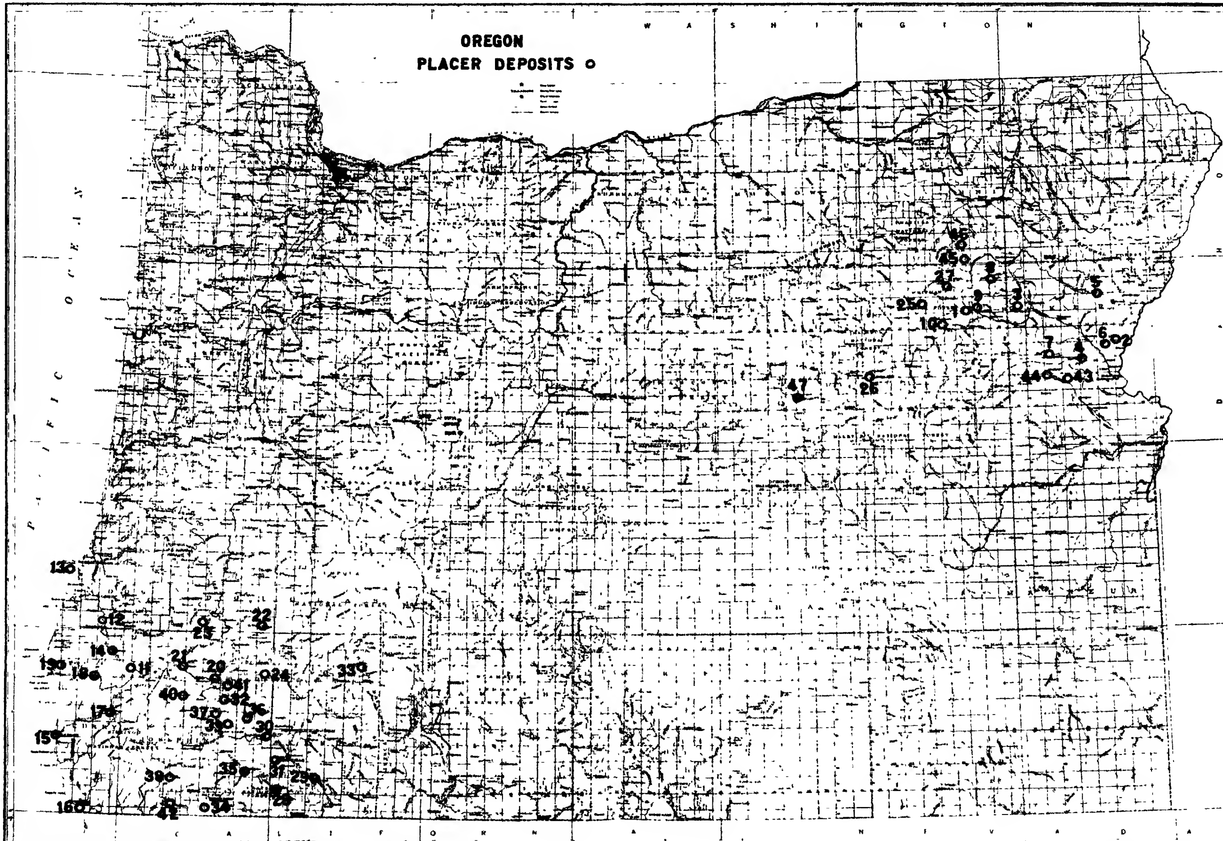
Mines, Location of, Subject to What Prior Right

Any location of any mining claim made upon any natural stream, or contiguous or near to any placer mine, or upon or below the dump of any placer mine, shall be subject to the prior right of all mines in operation prior to the making of such location, to discharge debris, gravel, earth, and slickens as the same was discharged, or may be

discharged, at the time of making such subsequent location of mining claim or claims.

Annual Assessment Work—Notice of to Co-Owners—Forfeiture of Interest

Whenever any quartz or placer mines shall be owned by one or more persons, companies, or corporations, or when any person, company, or corporation shall own any quartz or placer mines, in common with any other person, company, or corporation, any such person, company, or corporation owning an interest in said mine or mines, whether said interest be legal or equitable, shall have the right to perform the annual assessment work required by the laws of the United States and of the State of Oregon to be performed upon such mine or mines; such work, when so performed, shall, when it complies with the laws of the United States and of the State of Oregon, protect such mine or mines from relocation Upon the failure of any one of several co-owners or such mine or mines to contribute his proportion of the expenditures required in such assessment work, or to perform or pay for his or their proportion thereof, the co-owner or co-owners of such mine or mines who have performed or caused to be performed the said labor or assessment work, may, at the expiration of the year for which such assessment work was performed, give such delinquent co-owner or co-owners notice that the assessment work for said year has been performed, stating by whom performed, and the amount of work performed, and the dates between which the same was performed, together with a statement of the amount due from said delinquent co-owner or co-owners for his or their proportion of said assessment work, and requiring said delinquent co-owenr or co-owners, within ninety days from the date of the service of said notice, to pay to the co-owner or co-owners who performed or caused to be performed such assessment work, his or their proportion thereof. Such notice shall further state that if such delinquent co-owner or co-owners shall fail or refuse to contribute his or their proportion due for the said assessment work, his or their interest in said mine or mines will become the property of such co-owner or co-owners who have performed or caused to be performed such assessment work.


OREGON
PLACER DEPOSITS o
WASHINGTON
IDAHO
NEVADA
CALIFORNIA
PACIFIC OCEAN

Mining Claims May Be Located on State Lands

The manner of locating a mineral claim upon the state land shall be in accordance with the law of the state regulating the location of mineral claims on government lands; provided, that any citizen or citizens who may have found minerals on unsold state lands previous to the passage of this act, and posted notices in accordance with the laws of the state of Oregon and the United States, shall have preference right to lease the same, and shall have 90 days after the passage of this act, in which to make application to the state land board for such lease.

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For List of Equipment Needed See Page 55.

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Lincoln, F. C., and others, Placer mining number of "The Black Hills Engineer," South Dakota State School of Mines, Rapid City, South Dakota, Vol. 19, No. 4, 1931.

LIST OF PROSPECTOR'S EQUIPMENT

The following has been taken from a list prepared by the Northwest Mining Association, Spokane, Washington. This is not as complete a list as the one mentioned above.

When considering this list a prospector will, of course, take into consideration his personal requirements, tastes, etc. and particularly in the case of the large number of placer miners who are outfitting at the present time with a limited supply of money, they will base the amount of their purchases according to what they can afford.

The food supply contains those items which are in many cases light to carry and offer the greatest sustenance value. The amount estimated to be required for one person for three months is marked by figures after some foods which are more commonly used.

Mining Tools and Supplies.

- Hand saw
- Shovels
- Files
- Picks
- Hammer
- Nails and spikes
- Axes (single bitted)
- Whetstone
- Gold pans
- Quicksilver

Food Supply.

- Bacon (12 lbs.)
- Flour (50 lbs.)
- Milk (dried) (20 lbs.)
- Sugar (20 lbs.)
- Salt (4 lbs.)
- Coffee (2 lbs.)
- Butter (canned or salted) (10 lbs.)
- Eggs (dried) (3 lbs.)

Dried Food

- Prunes (8 lbs.)
- Potatoes (dessicated) (10 lbs.)
- Onions (10 lbs.)
- Beans (30 lbs)
- Rice (20 lbs)
- Oat meal (20 lbs.)
- Corn meal (10 lbs.)
- Baking powder (5 lbs.)
- Baking soda (1 lb.)

Canned Food

- Tomatoes
- Corn
- Beans
- Corned beef

Other Equipment and Supplies.

- Compass
- Match box (metal)
- Magnet (horse-shoe)
- Location notice blanks
- Magnifying glass
- Jack knife
- Paper and indelible pencil
- Fishing tackle

Cooking Utensils.

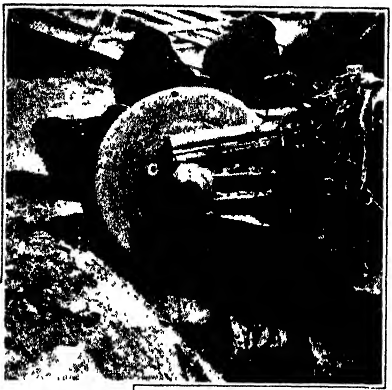
- Wash pan
- Frying pan (long handle)
- Bake pan
- Pots (with bails)
- Plates
- Cups
- Spoons
- Forks
- Knives
- Dish towels

Personal Effects.

- Clothing
- Matches
- Soap
- First Aid supplies

Relief Map of the State of Washington.

Bucket of Dredge



Placer Mining in
Swauk District

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State College of Washington

7. Thawing Frozen Water Pipes Electrically.
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8. Use of Ropes and Tackle, Illustrated.
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9. Well and Spring Protection.
By M. K. Snyder, July, 1922.

10. Water Purification for the Country Home.
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11. Farm Water Systems.
By M. K. Snyder and H. J. Dana, January, 1923.

12. Commercial and Economic Efficiency of Commercial Pipe Coverings. By H. J. Dana, January, 1923.

13. Critical Velocity of Steam with Counter-Flowing Condensate. By W. A. Pearl and Eri B. Parker, February, 1923.

14. The Use of Power Fans for Night Cooling of Common Storage Houses. By H. J. Dana, December, 1923.

15. A New Stationary Type Laboratory Meter.
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16. Relation of Road Surface to Automobile Tire Wear. First Progress Report. By H. V. Carpenter and H. J. Dana. January, 1924.

17. Relation of Road Surface to Automobile Tire Wear. Second Progress Report. By H. J. Dana, December, 1925.

18. Relation of Road Surface to Automobile Tire Wear. Third Progress Report. By H. J. Dana, October, 1926.

19. Rhythmic Corrugations in Highways.
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20. How to Measure and Use Water for Irrigation.
By O. L. Waller, March, 1927.

21. Magnetic Nail Picker for Highways.
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22. Spray Residue and Its Removal from Apples.
By F. D. Heald, J. R. Neller and F. L. Overley of the Agricultural Experiment Station in Cooperation with H. J. Dana.

23. Survey of Fruit Packing Plants. (Out of Print).
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24. Survey of Fruit Cold Storage Plants. (Out of Print.)
By H. J. Dana, March, 1928.

25. An Extensometer and Compressometer of the Hydro-Static Type.
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26. A Survey of Fruit and Cold Storage Plants in Central Washington.
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31. Rhythmic Corrugations in Highways. Second Progress Report. By Homer J. Dana, January, 1930.

32. The Economical Distribution of Steam in District Heating. By A. C. Abell, February, 1920.

33. Application of Stellite to Agricultural Tools. First Progress Report. By G. E. Thornton and C. C. Johnson, September, 1929.

34. A Study of Welded Metals Under Fatigue Tests. By G. E. Thornton, April, 1930.

35. Electro-Hydrometallurgical Process for Copper Flotation Concentrate. First Progress Report. By Arthur E. Drucker and Carl F. Floe, April, 1930.

36. Rhythmic Corrugations in Highways. Third Progress Report. By Homer J. Dana, December, 1930.

37. A Method of Compiling Approximate Mining Cost Data. By Guy E. Ingersoll, October, 1931.

38. Electro-Hydrometallurgical Process for Copper Flotation Concentrate. Second Progress Report. By Carl F. Floe and Arthur E. Drucker. January, 1932.

39. Fuel Economy in Domestic Automatic Heating. By Homer J. Dana and Howard H. Langdon, June, 1932.

40. Hand Methods of Placer Mining and Placer Mining Districts of Washington and Oregon. (Out of Print). By Guy E. Ingersoll, June, 1932.

41. The Relative Lubricating Value of Automotive Oils. By Howard H. Langdon, March, 1933.

42. Laboratory Methods of Comparing Lubricating Values of Automotive Oils. By H. H. Langdon, March, 1933.

43. Small Scale Methods of Placer Mining and Placer Mining Districts of Washington and Oregon. By Guy E. Engersoll, April, 1933

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

« « « PULLMAN, WASHINGTON » » »

VOL. XVII MARCH, 1935 NO. 10

ELECTRIC HOUSE HEATING SERIES, No. 1

Comparative Heat Loss Tests on Insulated and Un-insulated Buildings in the Electrified Mason City at Grand Coulee Dam Site

by Homer J. Dana
Assistant Director, Engineering Experiment Station

and R. E. Lyle
Engineer of Tests at Mason City

Report Presented to
WASHINGTON STATE PLANNING COUNCIL
May 25, 1935

ENGINEERING BULLETIN NO. 45
ENGINEERING EXPERIMENT STATION
H. V. Carpenter, Director

PUBLISHED BY THE STATE COLLEGE OF WASHINGTON

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911 This was followed by later appropriations In April, 1919, this department was officially designated, Engineering Experiment Station

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington The work of the station is made available to the public through technical reports, popular bulletins, and public service The last named includes tests and analyses of coal, tests and analyses of road materials, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc

Bulletins are available on pages 25 and 26

Requests for copies of the engineering bulletins and inquiries for information on engineering and industrial problems should be addressed to The Engineering Experiment Station, State College of Washington, Pullman, Washington

The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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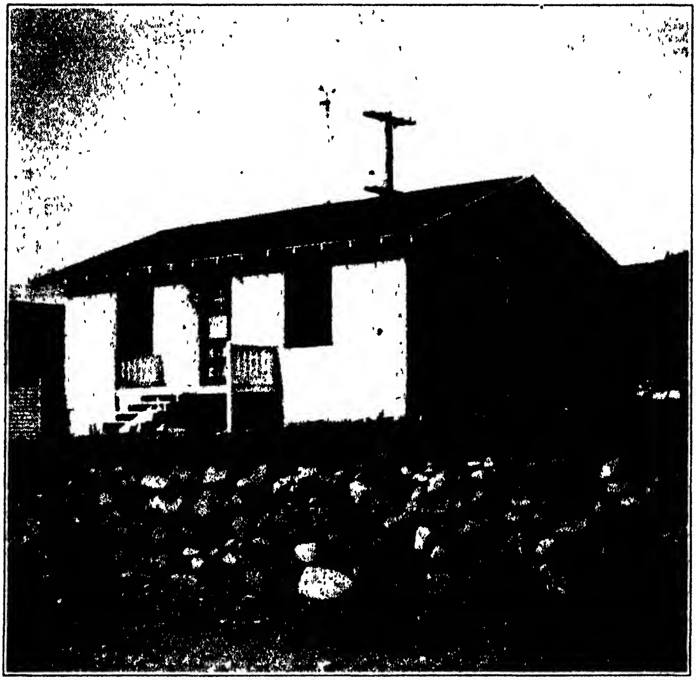
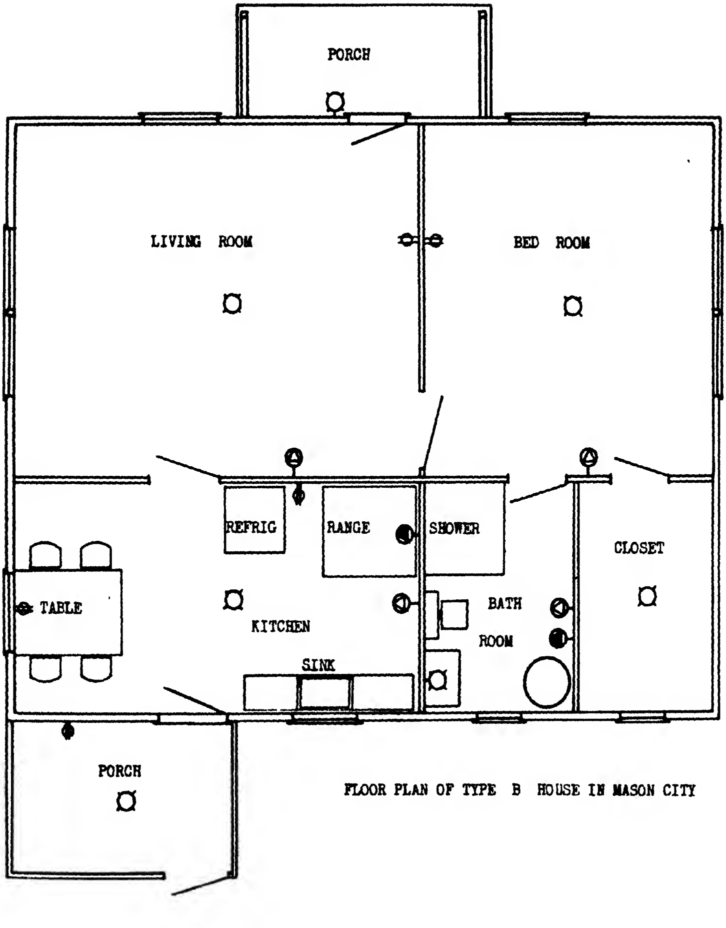


One of the Type B houses in Mason City which was specially insulated for these tests.



FLOOR PLAN OF TYPE B HOUSE IN MASON CITY

Preface

The decision by the Mason-Walsh-Atkinson-Kier Company, the contractors for the construction of the Grand Coulee dam, to use electricity for heating as well as for all other appropriate uses in the contractor's camp known as Mason City on the Grand Coulee Dam Site on the Columbia River, automatically created the largest house heating laboratory in the world[1] Mason City was built without a stove or furnace chimney in any of the 286 residences and more than 60 bunk houses and dormitories Residence heating is 100% electrical

The scope of the work undertaken in this laboratory includes studies of four general subjects related to the household use of electricity:

1. Thermal building insulations
2. Heat storage for using off-peak power
3. Summer air conditioning
4. Domestic heating as a system load

This bulletin is a progress report, and is No 1 of this series of studies. Reports on the remaining subjects will follow as rapidly as the work can be completed.

[1] Through the courtesy of the Mason-Walsh-Atkinson-Kier Co., The State College of Washington, was accorded the privilege of using this 100% electrified town as a field laboratory for studying domestic heating with electricity, making tests on thermal building insulations, making tests on methods of heat storage, studying the subject of summer and winter air conditioning, etc

Much appreciation is due the Mason-Walsh-Atkinson-Kier Co and to Mr Juan Hargrove, Architect, for aid in preparing for specially insulating certain of the houses for the tests

Comparative Heat Loss Tests on Insulated and Un-Insulated Buildings in the Electrified Mason City at Grand Coulee Dam Site[2]

By

Homer J. Dana and R. E. Lyle

INTRODUCTION

The amount of heat required to maintain a comfortable living temperature in a residence depends upon the outside temperature and the degree to which the structure is insulated against heat losses. In most residences, which are heated with coal or gas, but very little thought has been given to insulating against preventable heat losses, with the result that needless extravagance in fuel is incurred each year. Tests have been made which show that the investment required to properly insulate the average residence will be returned in the cost of fuel saved within a period of three years.[3]

Strangely enough, the need for heat insulation is commonly neglected in coal and gas heated homes but is readily recognized when associated with electrical house heating. The need for insulation, and the economies possible are almost equally as important in the one case as in the other.

The object of the study embraced by this report is to determine the actual average working effectiveness of applying heat-insulating material to an un-insulated house. The fundamental heat conductivity of insulating materials is known or may be easily determined. Furthermore, it is not a difficult matter to calculate the heat loss which will take place through certain combinations of materials such as go to make up the walls, floors, and ceilings of a house. But such calculations must necessarily be based upon certain assumed data which can-

[2] This work was made possible through the cooperation and assistance of the Washington State Planning Council, the Columbia Basin Commission, and the W E R A

[3] U. S. Bureau of Industrial Research

not easily be predetermined. For instance, the loss due to "chimney action" in air spaces in the wall, emissivity of the wall surfaces, variation in temperature between floor and ceiling of the room, degree of infiltration taking place, etc, are usually approximated and may vary considerably under different conditions.

MASON CITY AS A LABORATORY

In addition to more than 60 dormitories and bunk houses, Mason City is composed of a large number of houses located on a level plateau along the east bank of the Columbia River, of types as follows:

64 Type "A" or one-room houses
127 Type "B" or three-room houses
88 Type "C" or five-room houses
7 Special houses for officials.

Studies were confined primarily to the Type "B" houses because there are so many of them, they are heated with identical equipment, and occupied by average families These houses are pre-fabricated frame construction, built at Spokane, Washington, and trucked in sections 100 miles to the site where they were erected.

The Type "B" houses, on which these insulation tests were made, are approximately 20 x 28 feet in size, are set on concrete piers, and boxed clear to the ground, after which they were banked with earth, thus sealing the space under the floors against cold winds The side walls are of ¾" sheathing, tar paper, and matched siding The roof is of ¾" ship lap covered with red roofing felt On the inside, all walls and ceiling are finished with ½" INSOBOARD which is a wheat straw product This material, which comes in large sheets, is nailed to the 2 by 4 studding and ceiling joists, and the joints are covered with thin wooden strips or battens The floors are of double thickness with tar paper between. There are no basements and all residences are single story. There is a small space between the ceiling and the roof, with vent louvres in each gable.

Three-wire electrical service to each house provides 120 volts for lights and refrigeration, 120-240 for the electric range, and 240 for the electric air heaters, and for the water heater. The water heater, of

the clamp-on type, is thermostatically controlled. Air heating is accomplished with portable heater units located in each room. Provision was made for capacities as follows:

Living room	5 KW
Kitchen	3 KW
Bedroom	4 KW
Bath	1½ KW

With such a large number of houses available which were identical in size, construction, and type of heating, an excellent opportunity was afforded to study the actual effectiveness of applying additional heat insulation. Therefore, extensive tests were undertaken in order to obtain data on the comparative heat losses in un-insulated houses and in specially insulated houses. The type "B" house was chosen for these tests. It has living room, kitchen, bedroom, bathroom, and large closet At the rear is an enclosed porch for laundry, etc.

Two of these dwellings were chosen as check houses, representing a very common type of construction without special heat insulation Other houses of the same size and type, and located in the same group were equipped with special insulation intended to reduce the heat losses through the walls and ceiling of the building

HEAT INSULATIONS

There were six different kinds of building insulation employed in the tests[4] No attempt was made to evaluate any one insulation as against another, but rather to determine the actual heat insulating value of each when applied to an un-insulated house. The economic value of each as applied depends upon costs which may be obtained from supply houses The general description of these materials follows:

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[4] Special mention should be made of, and appreciation expressed to the companies which participated by supplying insulating materials for these tests The Reynolds Metals Co, through their representatives, The Building Supplies Co. of Spokane, furnished "Metallation" insulation for two houses The Northwest Magnesite Co, through Spokane Paper & Stationery Co. of Spokane, furnished "Thermax" insulation for two houses. C A Grennel & Son, of 918 S. Walnut St., Spokane, Washington, furnished enough "Diatomite" for two houses. James Keeth, E. 1827 Sprague Ave, Spokane, furnished enough "Zonolite" insulation for two houses Eagle-Picher Sales Co. of Kansas City, Mo., supplied loose mineral wool for one house. The MWAK Co. furnished "Unifil" to treat two houses.

A "Thermax" consists of wood shavings impregnated with a solution of magnesite, slightly compacted and baked into a rigid slab. This slab is nailed to the studding and joists of a house and, in addition to its properties as a heat insulator, it serves, instead of lath, as a base for the usual plaster finish of a room The inner surface of all exterior walls and ceilings of the two test houses were treated with 1" of Thermax which was also plastered No INSOBOARD was used in these houses The resulting wall was composed of ¾" siding, tar paper, ¾" sheathing, 3½" air space, 1" Thermax, and ½" plaster

B "Metallation" consists of a heavy craft paper approximately 01" thick and coated on each side with bright aluminum foil approximately 0015" thick, and cemented on This material in sheet form, 24 to 30 inches wide, was nailed direct to the edge of the ceiling joists and the exterior wall studding in the room Three-quarter inch firring strips were next applied and to these was nailed the standard ½" INSOBOARD finish of the houses The section of the insulated wall, therefore, included outside pine siding, tar paper, sheathing, 3½" air space, metallation, ¾" air space, and ½" INSOBOARD

C "Mineral wool," made in this case from lead slag, consists of finely spun threads loosely packed into the air spaces of the outside walls and ceiling Its insulating value rests largely in its ability to subdivide the air space and prevent the circulation of the entrapped air The resulting wall consists of siding, tar paper, sheathing, 3½" mineral wool, and INSOBOARD The ceiling was covered with 3" mineral wool This building had a cement basement, ceiling of which consisted of ½" INSOBOARD

D "Zonolite" consists of a non-metallic ore possessing bright flakelike characteristics similar to sheet mica When subjected to certain heat treating processes, the ore is greatly expanded in volume, resulting in a large volume of entrapped air finely subdivided The usual air spaces in outside walls were filled with this material, resulting in a section composed of siding, tar paper, sheathing, 3½" zonolite, and ½" INSOBOARD Ceilings were covered with 3" of zonolite.

E. "Unifil" consists of a non-metallic ore which when processed, results in a bright, light weight, flaky substance resembling mica, or

muscovite. When expanded in the heating process, these flakes partly separate, thus entrapping air in finely subdivided layers. This material was applied to fill the air spaces in outside walls and ceiling of one of the standard test houses, and to fill the ceiling only of another test house. Thickness on ceilings was 3″.

F. "Diatomite," as prepared for use as a building insulation, comes in finely powdered form. It consists of tiny lime skeletons of prehistoric water life, which are porous and entrap air in exceedingly small subdivisions This material was applied to the ceiling only of two of the standard test houses Thickness was 2″ and 3″ respectively

METHODS OF TEST

A standard routine was followed in making all of the radiation tests Several hours before the tests were begun the electric heaters were adjusted to maintain the temperature in the house uniform throughout Thermometers were located in each of the rooms at a point approximately 5 feet from the floor and were always located at the same relative points in all of the houses tested Adjustable heater units of the Wesix portable dynamic type were distributed throughout the house in such a way as to aid in the establishment of a uniform temperature A special auto-transformer with taps was provided to control the voltage to one of the heaters to afford fine adjustment of input Electric fans were provided at certain points in the different rooms to assure temperature uniformity Windows and doors were closed, window shades raised, and water heater disconnected The only furniture present, in most of the tests, consisted of a dining table and four chairs

The houses were heated from 2 to 8 hours, prior to recording data, using only enough of the installed heater capacity to hold the room temperature at or near 70 degrees Two houses were usually tested at one time, using two complete sets of equipment. The same equipment was used on the same house on succeeding tests Account was taken of the number and voltage of the lights burned in the house during the tests, and allowance was made for the heat given off by the man making the tests. Most of the closed tests were made at night because more uniform outside temperatures existed at that time.

By means of a graphic recording wattmeter connected into the electrical service to the building under test, record was made of the watts input to maintain a stable inside temperature. A special connecting device with cables to the instruments was used to permit locating the meters inside the house, and still have them connected into the service cabinet outside A special device admitted the necessary wires through the window without permitting air leakage into the room.

A recording thermometer with a temperature bulb exposed to the outside air some ten feet above the ground on the north side of the laboratory building gave a continuous record of the outside air temperatures during the test. A U.S. Weather Bureau anemometer gave a continuous record of wind velocity. Careful note was made of the wind direction.

Careful note was made that all windows and doors were properly closed and that there was no opportunity for excessive infiltration of air through cracks or crevices, or ill-fitting sash. Note was made each time an outside door was opened and care was taken to reduce the number of openings to a minimum.

When a stable condition had been established inside the building and a stable condition of wind and temperature existed outside, then the number of watts input represents the heat loss through the walls, floor, and ceiling of the building.

During each test the following data were taken: Outside temperature, wind velocity and direction, temperature in each room, electrical input, line voltage, number times door was opened, number lights burning, electrical connections, and observations as to weather.

The technique of making these tests was standardized to avoid variation in data on this account. Notes were made frequently on the wattmeter record during the test, citing any pertinent information. The curve on the record was corrected by means of a calibration curve and zero correction. Where frequent voltage fluctuation took place during a test, an integrated average was determined for the watts input during the test.

In those tests made on houses which were occupied by tenants, calculation was made of the heat supplied by the hot water tank, and from other sources, such as the reserve heat in an oven, etc.

Attempt was made to maintain all rooms in the house at the same temperature during the test. On this basis the direction of the wind should have scarcely any effect upon the heat loss through walls of the house. The difference in window exposure on different sides of the house, however, would cause the heat loss through the glass to depend somewhat upon wind direction. Inasmuch as there was not a wide difference in wind velocities in different tests, no attempt has been made to correct the data for this factor. The curve of radiation loss as drawn, tends to equalize the differences due to differences in wind velocity.

DISCUSSION OF TEST DATA

These tests were made possible through the cooperation of the firms which furnished the insulating materials. Some of the materials are recognized as not being such good heat insulators as others and results of the tests show some such differences On the other hand, there may be compensating features such as ease of installation, lower first cost, etc., which in the end, tend to equalize the economic value of the various materials submitted. After all, the object of these tests was to draw attention to the preventable heat loss from buildings and to show the saving that can be effected by the addition of insulating materials to the walls and ceiling of a residence.

As a matter of fairness to all contributing firms in this series of tests, the insulations are listed in the data as 1, 2, 3, 4, etc

The curve in Figure 1 shows the heat loss from the Standard Type B House as constructed in Mason City. This type building has double thickness floor with paper between; walls are siding, paper, sheathing, 3½" air space and ½" INSOBOARD, and ceiling of ½" INSOBOARD nailed to 2 x 4 ceiling joists. The roof is ¾" sheathing with roofing felt finish. The attic space was not ventilated during these tests.

It is difficult in making a radiation test on any building to find a time when weather conditions are absolutely stable. Furthermore, identical conditions of wind direction and velocity, and air humidity do not always exist during succeeding tests. If certain conditions of weather could be duplicated in succeeding tests, then the data would

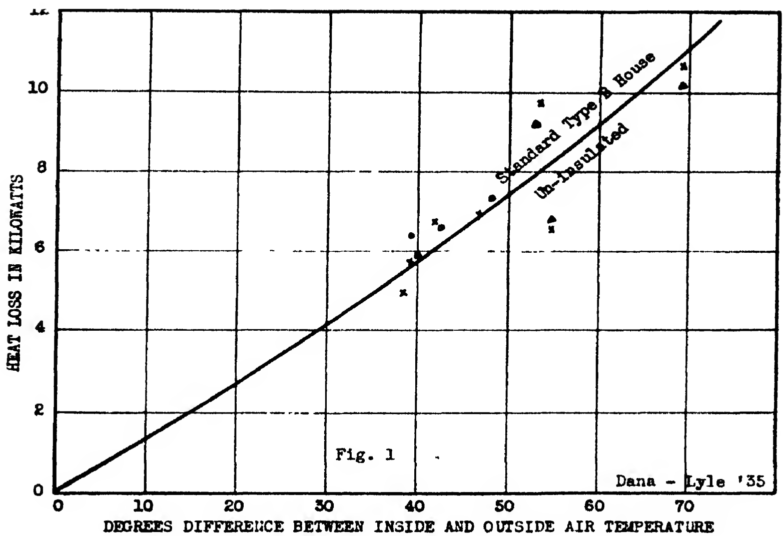
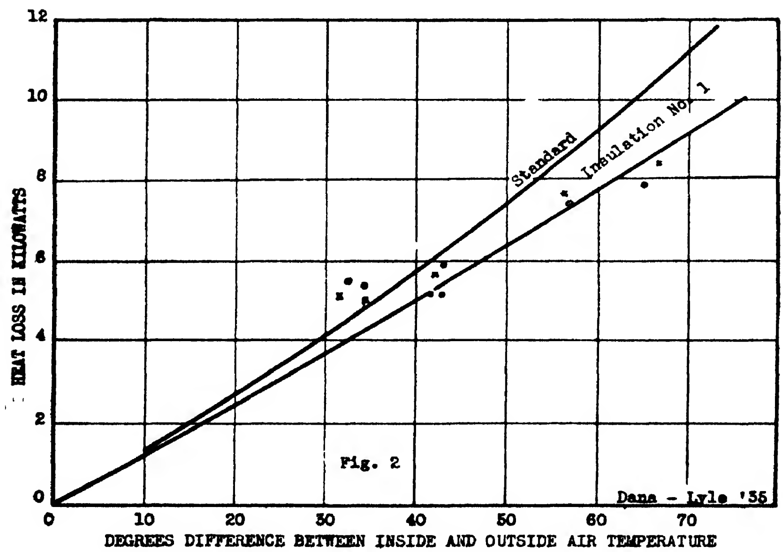

HEAT LOSS IN KILOWATTS
DEGREES DIFFERENCE BETWEEN INSIDE AND OUTSIDE AIR TEMPERATURE
Standard Type B House
Un-Insulated
Dana - Lyle '35

Fig. 1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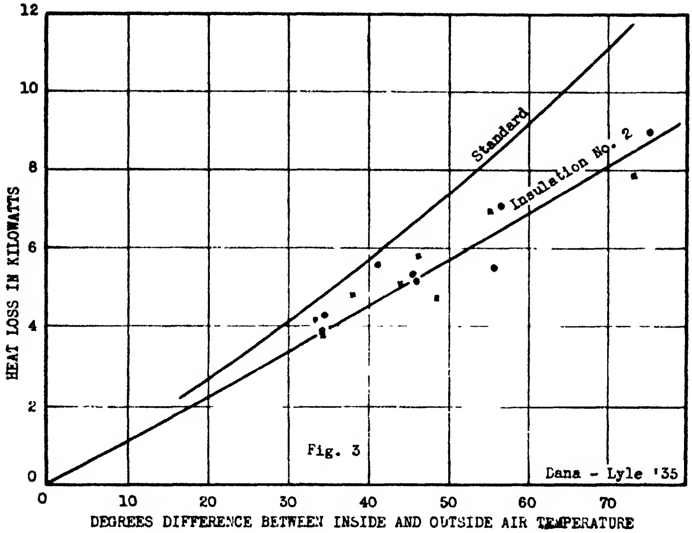
DEGREES DIFFERENCE BETWEEN INSIDE AND OUTSIDE AIR TEMPERATURE
Standard
Insulation No. 1
Dana - Lyle '35

Fig. 2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DEGREES DIFFERENCE BETWEEN INSIDE AND OUTSIDE AIR TEMPERATURE
Standard
Insulation No. 2
Dana - Lyle '35

Fig. 3

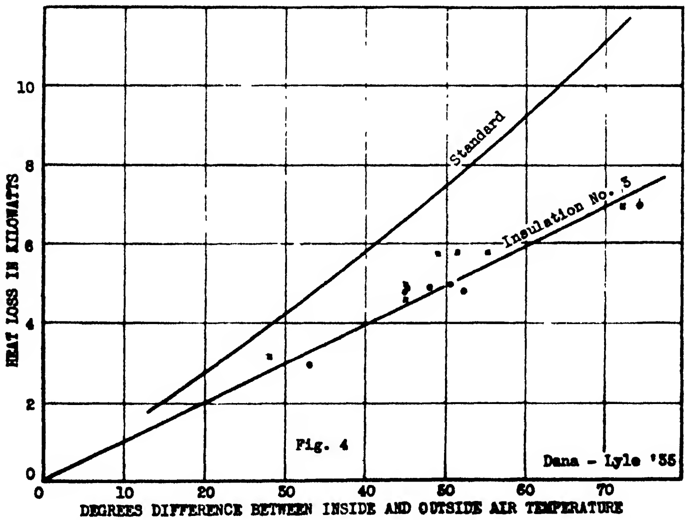

HEAT LOSS IN KILOWATTS
DEGREES DIFFERENCE BETWEEN INSIDE AND OUTSIDE AIR TEMPERATURE
Standard
Insulation No. 3
Dana - Lyle '35

Fig. 4

lie close to an average curve. Lacking these ideal conditions the next best alternative is to make tests under as nearly uniform conditions as possible. Although this was done, the data obtained is somewhat scattering, but the average, as represented by the curve, is thought to be reasonably accurate.

In the following figures, comparison is made between the heat loss through the walls and ceiling of a standard house as compared to the heat loss through other houses of the same size and type, the walls and ceiling of which were specially treated with different types of insulation. The curves represent an average of the data obtained.

As an illustration of the value of insulation, take the case shown in Figure 4. The heat loss from the insulated building at a 60 degree difference of temperature between inside and outside is 5,950 watts. The heat loss from the uninsulated building is 9,100 watts, or a difference of 3,150 watts. If the insulated house were operated for two weeks during which time the outside temperature remained 10 above zero and the inside temperature was maintained at 70 for fourteen hours per day, the saving of heat would amount to 617.4 kilowatt hours.

Taking a coal furnace as being 50% efficient, which by the way, is probably better than the average, and based on coal at 14,000 BTU per pound as fired, the use of the No. 3 insulation would save 300 pounds of coal during the above two weeks operation.

By taking the average outside temperature of different periods of the year during which heat is needed in a residence, it would be possible to calculate the yearly saving due to the added insulation, and from this figure could be derived the net saving from a given investment in heat insulation. This does not take into account any other factors, such as comfort or healthful living conditions, which might increase the returns from applying heat insulation. For instance, the annual average mean temperature in the Inland Empire region for the heating season is approximately 35 degrees Fahrenheit. Assume 200 heating days at this average temperature maintained for 14 hours per day. Then the saving in coal on the above basis, would be 2050 pounds for a house of the size used for these tests. When heated electrically, and on the same basis, the saving due to the No. 3 insulation would amount to 4,200 KW hours.

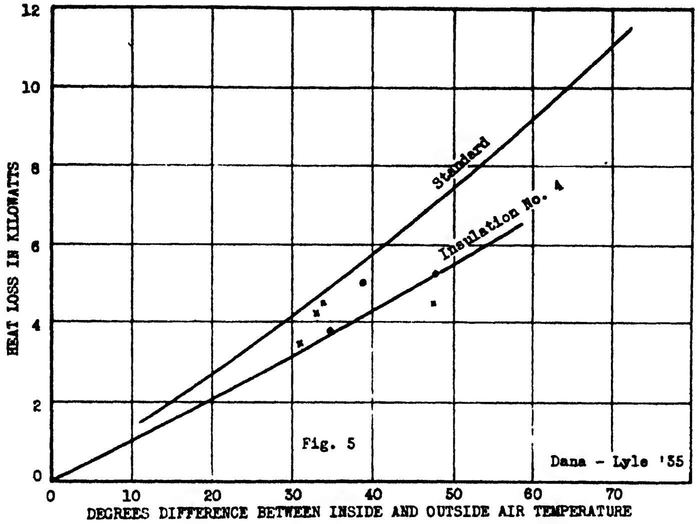
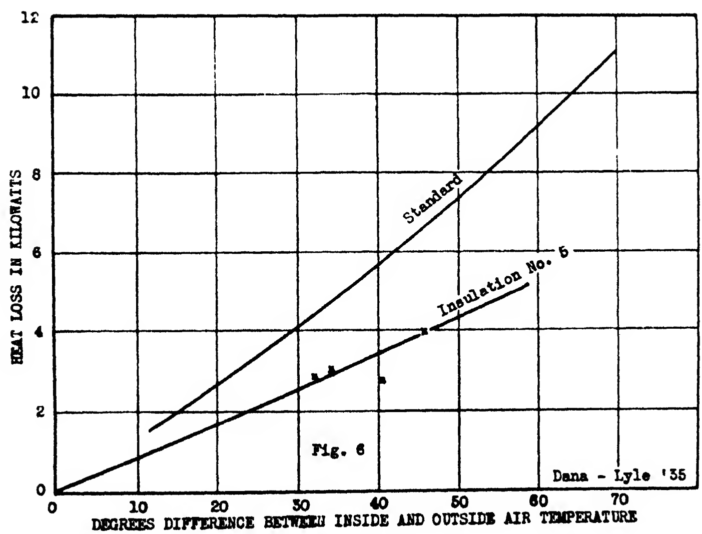

12
10
8
6
4
2
0
HEAT LOSS IN KILOWATTS
0
10
20
30
40
50
60
70
DEGREES DIFFERENCE BETWEEN INSIDE AND OUTSIDE AIR TEMPERATURE
Standard
Insulation No. 4
Dana - Lyle '35

Fig. 5


12
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8
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4
2
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HEAT LOSS IN KILOWATTS
0
10
20
30
40
50
60
70
DEGREES DIFFERENCE BETWEEN INSIDE AND OUTSIDE AIR TEMPERATURE
Standard
Insulation No. 5
Dana - Lyle '35

Fig. 6

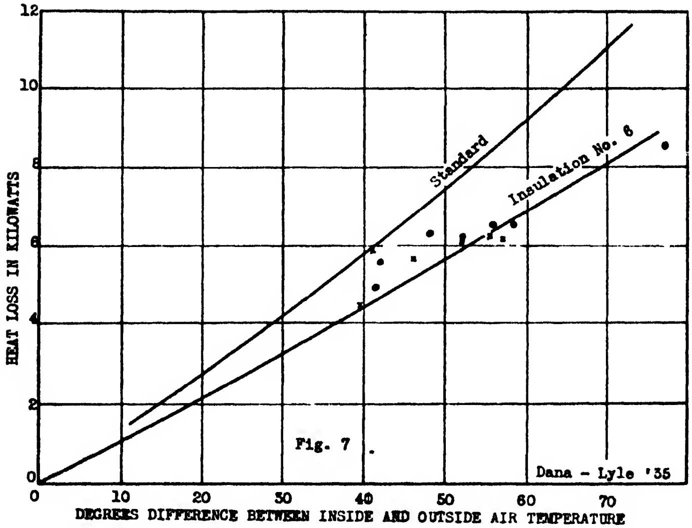
HEAT LOSS IN KILOWATTS
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
DEGREES DIFFERENCE BETWEEN INSIDE AND OUTSIDE AIR TEMPERATURE
Standard
Insulation No. 6
Dana - Lyle '35

Fig. 7

TEST DATA

Date	Time	Test No.	Record No.	Temperatures Outside	Inside	Diff.	Wind Vel.	Direction	K.W. Input	W/Deg. F.
Insulation No. 1a										
Jan. 1	11:30 P.M.	A-14	EA-2	36	70	34	11	S E	4.975	146.2
Jan. 4	8 00 A.M.	A-16	EA-2	38	69½	31½	9	S E	5.060	160.6
Jan. 7	7:30 A.M.	A-18	EA-2	28	69½	41½	4	NE	5.105	123.2
Jan. 13	12.30 A.M.	A-34	EA-2	28½	70½	42	8	S E	5.590	133.0
Jan. 17	9:30 P.M	A-58	EA-2	14	70½	56½	8	NE	7.640	135.1
Jan. 18	7.30 A M.	A-60	EA-2	6	72½	66½	16	NE	8.155	122.6
Insulation No. 1b										
Jan. 1	12:30 P M.	A -15	GE-1	36	70½	34½	11	S E	5.355	155.2
				37	71½	34½			5.550	160.9
Jan 4	8·30 A.M.	A-17	GE-1	38	70½	32½	9	S E	5.425	166.8
Jan. 7	7·30 A M.	A-19	GE-1	28	71	43	4	NE	5.885	136.7
Jan. 13	2:00 A.M	A-35	GE-2	28½	71	42½	8	S E	5 120	120.3
Jan 17	9:30 P M.	A-59	GE-2	14	71	57	8	NE	7.410	130.0
Jan. 18	7:30 A M.	A-61	GE-2	6	71	65	16	NE	7.875	121.0
Insulation No. 2a										
Dec. 19	11:30 P M	A- 2	EA-1	36	70	34	—	SW	3.845	113.0
Dec. 26	11·30 P.M	A- 9	EA-1	24	70	46	—	none	5.730	124.5
Jan 12	9:30 P.M.	A-32	EA-2	28	72	44	6	S E	5.095	115.7
Jan. 14	5:00 A.M	A-40	EA-2	15	70	55	15	NE	6.935	126.0
Jan 16	11·00 P.M.	A-54	EA-2	33½	71½	38	13	SW	4.790	126.0
Jan. 17	8:00 A M.	A-56	EA-2	21	69½	48½	4	S-SW	4.760	98.2
Jan. 19	9:00 A.M.	A-66	EA-2	—2	71	73	11	N-NW	7.840	107.3
Jan. 23	10:30 P.M.	A-77	EA-2	37	70½	33½	11	SW	4.130	123.3

TEST DATA

Date	Time	Test No.	Record No.	Temperatures Outside	Temperatures Inside	Temperatures Diff.	Wind Vel.	Wind Direction	K.W. Input	W/Deg. F.
Insulation No. 2b										
Dec. 19	11:30 P.M.	A- 1	GE-1	36	70	34	—	SW	3.900	114.6
Dec. 26	11:00 P.M.	A- 8	GE-1	24	70	46	—	none	5.095	110.6
Jan. 12	10:00 P.M.	A-33	GE-2	28	73½	45½	6	S E	5.235	115.0
Jan. 14	5:00 A.M.	A-41	GE-2	15	71½	56½	15	NE	7.005	124.0
Jan. 16	11:00 P.M.	A-55	GE-2	33½	74½	41	13	SW	5.500	134.0
Jan. 17	8:00 A.M.	A-57	GE-2	21	76½	55½	4	S-SW	5.460	98.5
Jan. 19	9:00 A.M.	A-67	GE-2	—2	73	75	11	N-NW	8.990	119.8
Jan. 23	10:30 P.M.	A-78	GE-2	37	71	34	11	SW	4.255	125.1
Insulation No. 3a										
Dec. 20	10:30 P.M.	A- 3	EA-1	42	70	28	—	none	3.120	111.4
Dec. 28	12:30 A.M.	A-11	EA-1	25	70	45	5	NE	4.835	105.0
Jan. 13	9:00 P.M.	A-36	EA-2	22	71	49	15	NE	5.675	115.7
Jan. 15	9:30 P.M.	A-48	EA-2	20	71½	51½	6	NE	5.785	112.3
Jan. 16	7:30 A.M.	A-50	EA-2	21	76	55	4	NE	5.790	105.2
Jan. 18	11:00 P.M.	A-64	EA-2	—2	70	72	10	NE	6.935	96.4
Jan. 22	10:00 P.M.	A-74	EA-2	26	71	45	4	NE	4.535	100.8
Insulation No. 3b										
Dec. 21	10:30 P.M.	A- 4	GE-1	37	70	33	—	none	2.985	90.5
Dec. 27	11:30 P.M.	A-10	GE-1	25	70	45	5	NE	4.720	102.7
Jan. 13	8:30 P.M.	A-37	GE-2	22	70	48	15	NE	4.850	101.0
Jan. 15	9:30 P.M.	A-49	GE-2	20	72	52	6	NE	4.775	91.9
Jan. 16	7:30 A.M.	A-51	GE-2	21	71½	50½	4	NE	4.910	97.4
Jan. 18	11:00 P.M.	A-65	GE-2	—2	72	74	10	NE	6.920	93.6
Jan. 22	10:00 P.M.	A-75	GE-2	26	71	45	4	NE	4.870	108.1
Insulation No. 4a										
Dec. 21	10:30 P.M.	A- 5	EA-1	37	70	33	Light	SW	4.135	125.2
Dec. 22	10:30 P.M.	A-6	EA-1	39	70	31	Light	SW	3 415	110.0
Dec. 28	10:00 P.M.	A-12	EA-1	36	70	34	9	SW	4.425	122.8
Jan. 22	12:00 P.M.	A-76	EA-2	26	73½	47½	4	NE	4.400	92.6
Feb. 5	12:00 P.M.	A-81	EA-2	31	80	49	6	N-NE	6.390	130.3

TEST DATA

Date	Time	Test No.	Record No.	Temperatures Outside	Inside	Diff.	Wind Vel.	Direction	K.W. Input	W/Deg. F.
Insulation No. 4b										
Jan. 31	10:00 P.M.	A-79	EA-2	31	70	39	4	NE	4.915	126.1
Mar. 29	10:30 P.M.	A-82	EA-2	35	70	35	11	NW	3.795	108.4
Mar. 30	6:30 A.M.	A-83	EA-2	26	74	48	4	NE-E	5.100	106.3
Insulation No. 5a										
Dec. 26	11:00 P.M.	A- 7	GE-1	38	70	32	Light	SW	2.865	89.6
Dec. 28	10:30 P.M.	A-13	GE-1	36	70	34	9	SW	3.020	88.9
Jan. 31	10:30 P.M.	A-80	GE-2	31	71½	40½	4	NE	2.730	67.5
April 3	11:30 P.M	A-84	EA-2	31	77	46	4	NE-E	3.980	86.6
April 4	6:00 A.M.	A-85	EA-2	28	80	52	3	S	5.360	103 0
Insulation No. 6a										
Jan. 8	10:00 P M	A-22	EA-2	31	70½	39½	3	NE	4.445	112.4
Jan. 9	9:30 P.M.	A-24	EA-2	30	71	41	4	NE	5.910	144.0
Jan. 12	6:00 A.M	A-30	EA-2	24	70	46	6	S E	5.675	123.3
Jan. 14	9:30 P M.	A-44	EA-2	16	71½	55½	5	NE-E	6.240	112.3
Jan. 15	7:30 A.M.	A-46	EA-2	16	73	57	4	NE-E	6.190	108.6
Jan. 19	9:30 P.M.	A-68	EA-2	—4	70½	74½	3	NE-E	6.995	93.9
Jan. 21	9:00 P.M.	A-70	EA-2	19	71	52	2	NE	6.070	116.8
Insulation No. 6b										
Jan. 8	9:30 P M.	A-23	GE-2	31	72½	41½	3	NE	4.805	115.7
Jan. 9	9:30 P.M.	A-25	GE-2	30	72	42	4	NE	5.555	132 2
Jan. 12	6:00 A.M.	A-31	GE-2	24	72½	48½	6	S E	6.305	130.0
Jan. 14	9:30 P.M.	A-45	GE-2	16	71½	55½	5	NE-E	6.535	117.7
Jan. 15	7:30 A.M.	A-47	GE-2	16	74½	58½	4	NE-E	6.500	111.0
Jan. 19	9:30 P M	A-69	GE-2	—4	73	77	3	NE-E	8.565	111.2
Jan. 21	9:00 P.M.	A-71	GE-2	19	71	52	2	NE	6.065	116.6

TEST DATA

Date	Time	Test No	Record No.	Temperatures Outside	Inside	Diff.	Wind Vel.	Direction	K.W. Input	W/Deg.F.
Un-insulated House No. 8a										
Jan. 7	10:30 P.M.	A-20	EA-2	32½	71	38½	2	NE	4.850	126.0
Jan. 10	1:00 A.M.	A-26	EA-2	29½	71½	42	2	NE	6.770	161.0
Jan. 12	1:30 A.M.	A-28	EA-2	23	70	47	3	SE	6.955	148.0
Jan. 14	1:30 A.M.	A-38	EA-2	18	71½	53½	15	NE	9.675	180.7
Jan. 16	8:30 P.M.	A-53	GE-2	31	70½	39½	7	SW	5.625	142.3
Jan. 18	7:30 P.M.	A-62	GE-2	1	70½	69½	11	NE	10.660	153.5
Jan 21	11:30 P.M.	A-73	GE-2	16	71	55	4	NE	6.425	116.8
Un-insulated House No. 8b										
Jan. 14	1:00 A.M	A-39	GE-2	18	71	53	15	NE	9.115	172.0
Jan. 16	8:30 P.M	A-52	EA-2	31	71	40	7	SW	5.875	146.8
Jan. 18	7:30 P.M.	A-63	EA-2	1	70	69	11	NE	10.195	147.7
Jan. 21	12:00 P.M.	A-72	EA-2	16	71	55	4	NE	6.695	123.9
Un-insulated House No. 8c										
Jan. 7	9:00 P.M.	A-21	GE-2	32½	72	39½	2	NE	6.340	160.4
Jan. 10	1:00 A.M.	A-27	GE-2	29½	72	42½	2	NE	6.550	154.1
Jan. 12	2:30 A.M.	A-29	GE-2	23	71½	48½	3	SE	7.255	149.6

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OF THE STATE COLLEGE OF WASHINGTON

« « « PULLMAN, WASHINGTON » » »

VOL. XVIII JULY, 1935 No 2

ELECTRIC HOUSE HEATING SERIES, No. 2

The Feasibility of Using A Heat Storage Device for Domestic Heating with Electricity

by Homer J. Dana

Assistant Director, Engineering Experiment Station

and R. E. Lyle

Engineer of Tests at Mason City

Report Presented to

WASHINGTON STATE PLANNING COUNCIL

June 21, 1935

ENGINEERING BULLETIN NO. 46

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

PUBLISHED BY THE STATE COLLEGE OF WASHINGTON

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits" The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations In April, 1919, this department was officially designated, Engineering Experiment Station.

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Stanley A Smith, B S, Arch, Architectural Engineering

L. J Smith M E, Agricultural Engineering

Clare Chisman Todd, Ph D, Chemical Engineering.

Paul A Anderson Ph D, Physics

The Feasibility of Using A Heat Storage Device For Domestic Heating with Electricity[1]

By

Homer J. Dana and R. E. Lyle

INTRODUCTION

At the rates prevailing in most localities, electricity for air heating has not been able to compete with coal or oil When arguments are advanced for lower rates for heating based on larger units of consumption, the objection is made that lower rates are not justified because the peak of the heating load would be superimposed upon a badly peaked load, and therefore, might in some cases, give rise to an even worse load factor than exists at present If domestic heating could take power during the off-peak period, or if it could be controlled so that a high load factor could be maintained on the system, then some of the principal objections to domestic heating with electricity would have been met and a lower rate could be established for this type of load

Studies have been made by different investigators relative to the feasibility of storing heat from electricity in order to make use of off-peak power or to permit of a controlled load factor.

Water suggests itself as being one of the ideal storage media and considerable data have been obtained on this type of heat storage A well-insulated water tank with proper heating elements will store heat in a form which can be controlled and readily distributed Attached to a hot water radiator system and controlled by a thermostatic valve or by a circulating pump, thermostatically operated, heat can be delivered as required. The disadvantage of this system

[1] These tests were made possible through the interest and assistance of the Washington State Planning Council, the Columbia Basin Commision, and the W E. R A

Grateful appreciation is expressed to Mr B H Kizer, Chairman of the Washington State Planning Council for helpful criticism in the preparation of this report

arises from the fact that water cannot be heated above boiling point unless a pressure vessel is provided and equipped with proper safety devices Such necessary precautionary measures increase the cost of this type of storage and partly offset some of the advantages of using water.

Cast iron has been suggested as a storage medium and will serve admirably for the purpose Its principal disadvantage is a relatively high first cost Experiments have also been made using pea gravel in a metal container as a storage medium The details of construction of this device, which was built and tried in Germany, did not afford the desired control, with the result that the room became overheated at times.

Another type of heat storage consists of an insulated oven filled with brick or with rock In a locality where rock is available such an oven can be constructed at moderate cost The advantage of using brick or rock lies in the fact that either one can be heated to a relatively high temperature, say 500 to 600 degrees Fahrenheit, and therefore, the space requirements for the storage unit need not exceed the space occupied by the ordinary domestic furnace

HEATING LABORATORY AT MASON CITY, GRAND COULEE DAM SITE

When the decision was made to electrify Mason City, (the contractor's camp at the Grand Coulee Dam Site in the State of Washington) opportunity was given to the State College of Washington to use it as a field laboratory and to carry on an extensive series of studies relating to the use of electricity for domestic heating.[2] This laboratory, the largest of its kind in the world, consists of 286 residences and 61 bunk houses and dormitories, all heated 100 per cent electrically [3]

[2] Acknowledgement is made of the splendid cooperation afforded by the Mason-Walsh-Atkinsonn-Kier Company, contractors for the construction of the Grand Coulee Dam across the Columbia river, and owners of the model town called Mason City

Mr Juan Hargrove, architect of the 100 per cent electrified Mason City, also rendered valuable assistance in the design and building of the laboratory house, in which these tests were conducted

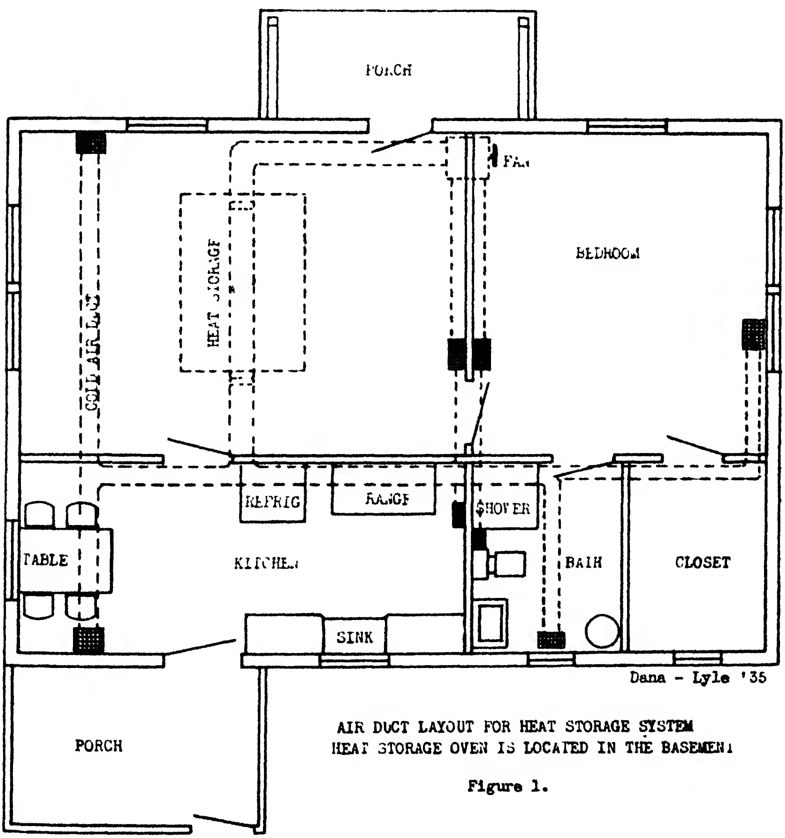
[3] See Engineering Experiment Station Bulletin No 45; "Study of Thermal Building Insulation at Grand Coulee Dam", by Homer J Dana and R. E Lyle, 1935.

SCOPE OF WORK UNDERTAKEN

The scope of work undertaken in this laboratory includes studies of four general subjects related to the domestic use of electricity:

1. Thermal insulation for buildings
2. Heat storage for using off-peak power.
3. Summer air conditioning.
4. Domestic heating as a system load

This report is No 2 of this series of studies and is a progress report of that part of the study completed at Mason City during the winter and spring of 1935



AIR DUCT LAYOUT FOR HEAT STORAGE SYSTEM
HEAT STORAGE OVEN IS LOCATED IN THE BASEMENT

Figure 1.

One of the Type "B" houses in Mason City was set up as a special laboratory for making tests of the feasibility of heat storage. A full basement, 20 by 28 was constructed under this house with walls and floor of concrete. A system of ducts and registers was laid out similar to that which would be employed in a hot air furnace installation in a residence of this type, and was connected to the heat storage device built in the basement (See Figure 1). Forced air circulation was employed, the fan being thermostatically controlled from the living room.[4]

HEAT STORAGE OVEN

The plan followed in section 2 of this investigation has been to study the feasibility of a storage device which would be simple and cheap to construct from materials easily obtainable in any locality, and which would also be simple to operate The first proposal was to build an insulated oven and fill it with brick checker work. However, this plan was abandoned in favor of using granite boulders, which were available within 50 feet of the basement in which the storage oven was built Basalt was considered, but the nearest supply was several miles away All three have approximately the same value of specific heat, therefore, no preference was felt on this point

THERMAL INSULATION FOR THE STORAGE OVEN

The object of a heat storage oven is to make use of electricity during one part of the day to furnish heat for a residence during some other part of the same day or of a succeeding day When electricity is used for direct heating, that is, the heat is used at the same time the electricity is being used to produce the heat, the transfer is 100 per cent efficient In other words, all of the electricity is made available in the form of heat Likewise, all of the electricity used to

[4] Special mention is made of the very fine assistance rendered by the Wesix Heater Co of Los Angeles, California They have furnished convection heaters, heating elements, thermostats, relays, time switch, and other material which were used in connection with tests on the storage oven.

Brandt Bros., of Spokane, Washington very kindly loaned a Buffalo fan for the air conditioning system

James Smyth Plumbing Company of Spokane rendered valuable assistance in the design and construction of the duct system in the laboratory house, and in furnishing materials for same

The U. S. Weather Bureau at Spokane very kindly loaned the use of an anemometer for determining wind velocities

charge the storage oven is converted into heat. However, some of this heat is radiated through the walls of the storage oven and escapes into the surrounding air without serving the purpose directly for which it was stored. Obviously then, the object would be to construct the storage in a fashion designed to reduce this heat loss to a minimum.

In a device employing temperatures up to 500 or 600 degrees Fahrenheit, it is apparent that an inorganic insulating material must be employed. There are materials available for this type of service, among them being diatomaceous powder, asbestos, mineral wool, and rock wool. The heat conductivity for mineral wool ranges between 261 and 300 BTU's.[5] Since a supply of mineral wool was available, this was the type of insulation chosen for the experimental oven, and was packed lightly into the space between the inner and outer walls.

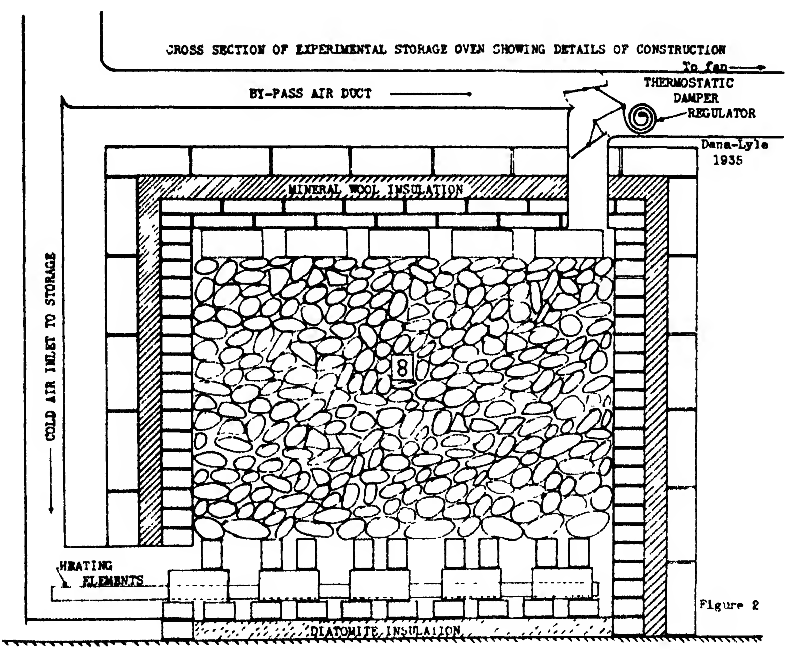


Figure 2

[5] Conductivity in BTU's per inch of thickness per square foot of surface per degree temperature difference per hour

The oven as constructed, (See Figure 2) consists of a 4-inch interior wall of brick laid up with mortar.[6] Outside of this wall and separated 3 inches from it is a 4-inch hollow tile wall with the space between the tile and brick wall filled with heat-insulating material On the floor of the oven was placed some two inches of diatomaceous earth in order to reduce the loss of heat into the concrete basement floor and from thence into the soil beneath. The diatomaceous earth in powder form was mixed with a small amount of Portland cement and water in order to make it solidify into a cake, and thereby prevent its being drawn up into the air duct system by the air drafts through the storage The space inside the oven was then filled with boulders ranging from 3 pounds to 60 pounds in weight.

DETERMINING THE SIZE OF THE STORAGE OVEN

The principal purpose of the heat storage oven is to reduce the peak demand on the electrical system The desired capacity depends upon the heat requirements of the house to be served, and upon the proportion of this load which the oven is called upon to carry For an uninsulated house, the heat requirements greatly exceed those of a house which is well insulated

Table 1 shows the measured heat loss through the walls, ceiling, and floor of the type B house in Mason City when the walls and ceiling are un-insulated, as compared with the heat loss from the same building with the walls and ceiling insulated by filling the air space with 3½" of mineral wool.[7] The actual ratio of heat loss in

Table 1. Heat Loss Through Typical Wall of Residence Double Board Siding, 3½" Studding, Lath and Plaster

Insulation between studding	Temperature difference between inside and outside	BTU'S heat loss per sq ft of surface per day
Air	50 deg	308
Mineral wool	50 deg	192

[6] The design of the storage oven as constructed was influenced partly by financial limitations and partly by lack of experience in the performance to be expected. It is hoped that revisions in design can be made and further data obtained under improved conditions during the winter of 1935-36

[7] See State College of Washington Engineering Experiment Station Bulletin No 45 by Homer J Dana and R E Lyle, 1935.

this case is 16 Obviously it is wise to make a substantial investment to insulate the walls and ceiling.

The laboratory house in which the experimental storage oven was built, was insulated on walls and ceiling with 3½ inches of mineral wool. It was estimated that the maximum daily heat required would not exceed one million BTU's for the coldest expected weather Therefore, the storage oven was designed for a useful capacity of one million BTU's at 600° F with an additional 690,000 BTU's available by raising the temperature to 900° This would make it possible to carry the entire daytime heating load on the storage oven On a practical basis, it might be desirable to carry only 4 to 6 hours of the load on the storage oven In that case, the size could be materially reduced.

CALCULATED HEAT STORAGE CAPACITY OF OVEN

It may be assumed that all material inside the insulation jacket can be considered as the heat storage medium The minimum affective temperature of operation was set at 170 degrees, and the maximum for this calculation at 600 degrees Fahrenheit Table II shows the quantities used in the oven and the data for calculating the heat storage capacity

Table 2

Weight	Material	Spec Heat	Temp rise 170 to 600	BTU Stored
7151 lbs	rock	20 BTU	430 deg	614,986
4314 lbs	brick	22 BTU	430 deg	408,104
492 lbs	clay	19 BTU	430 deg	40,196
11,957 lbs			Total	....1,063,286 BTU

1,063,286 BTU's represents an equivalent electrical energy of 312 kilowatt hours* During the charging of this oven, and running over its storage period and draw down period, there would be certain radiation losses. If we assume these to be, say, 7 per cent of the out-

*One kilowatt hour will produce 3415 BTU (British Thermal Units) One BTU is the heat required to raise the temperature of one pound of water one degree Fahrenheit It is also the equivalent of 778 foot pounds of work

put of the oven, then the total input would need to be 335 kilowatt hours. If we assume a charging period of ten hours, the input would be 33½ kilowatts, if 15 hours, then the input would be 22⅓ kilowatts. The percentage loss by radiation in each case would depend upon the storage temperature and the schedule of the charging and discharging cycle.

OVEN HEATER CONTROL

Provision is made for inserting the electric heater elements through a duct underneath this mass of rock so that when the electricity is turned on, the natural air circulation will carry away the heat and communicate it to the rocks in the oven. This heating up may be done at any desired time of the 24 hour day and ordinarily would be accomplished during the period when electricity is least needed for other purposes. By means of a switch controlled by a clock, carrier current, or other equivalent means, the heat may be turned on, say about 9:00 at night. A thermostat in the oven serves to turn off the heating elements when the temperature has risen to any predetermined value. The time switch is set to turn off the storage oven at 7:00 A.M , if the thermostat has not already turned it off due to the desired temperature having been reached earlier in the night. It is entirely feasible to heat this type of storage to 800 or 900 degrees or more Only 11½ k.w. of heater capacity was installed for the first tests, but provision is made for increasing this capacity for further tests next winter if found desirable

AIR DUCT SYSTEM

The duct system to the rooms is attached to this oven so that part of the cold air coming from the rooms enters near the bottom at one end. The hot air duct is attached to the top at the opposite end (See Figure 2). When the oven is fully charged, the temperature of the air inside would be 500 to 600 degress Fahrenheit. Such a high temperature is obviously undesirable in the ducts or in the room above. Therefore, provision is made for a by-pass duct around the oven through which most of the air from the rooms is circulated by the fan. Only enough air is drawn through the heat storage to bring the temperature of the air in the ducts to approximately 150

degrees. This is accomplished by means of an automatic thermostatically controlled damper adjusted to admit only the proper amount of hot air from the oven, mixed with the air in the by-pass to yield the desired temperature. The heating system in the oven is entirely independent of the air circulating system of the house. Furthermore, it would be entirely possible to turn on the heaters and draw heat through the storage oven into the house without first storing it, as would be done ordinarily. This would permit the house to be warmed, even though the storage oven were not charged

HUMIDIFIER

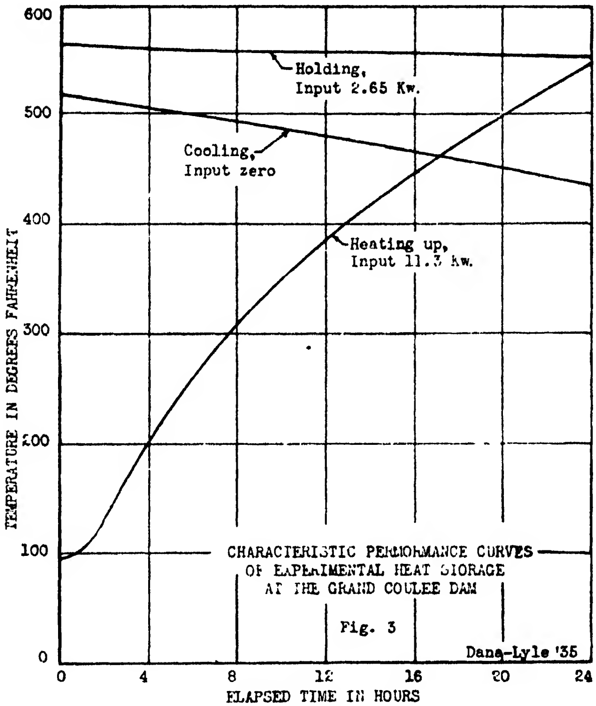
Under certain heating conditions it is frequently found desirable to introduce moisture into the air circulated into a living room There are various methods of accomplishing this. Use may be made of evaporation from pans of water or by some method employing spray nozzles. The method used in connection with these tests employed a humidifier of the motor driven centrifugal type The unit was entirely self-contained and introduced moisture into the air in a very finely atomized state A hygrostat located in the living room and connected to the humidifier motor will maintain the room humidity at any desired value

It may be explained that the addition of humidity is no more necessary in this type of heating than in any ordinary hot air type of furnace-heated home Moreover, this type of humidifying apparatus may just as easily be applied in a home heated by a coal or oil furnace of the hot air type

TESTS ON STORAGE OVEN

A 5 kilowatt heater was set up temporarily to blow warm air through the storage for several days after it was built in order to dry it out. Then the 11½ kilowatt heater elements were installed and turned on After several days further drying out, tests were made to determine the rate of heating up, and amount of loss by radiation Figure 3 shows the curves for this test. Temperatures were obtained by the use of copper-constantin thermo-couples, which were calibrated up to 600 degrees against a mercury thermometer After the oven had been heated up to working temperature, the input to the

heaters was adjusted to maintain this temperature uniformly. If the heaters are adjusted so that a stable temperature is maintained in the storage oven, then the input to the heater elements represents the heat



CHARACTERISTIC PERFORMANCE CURVES OF EXPERIMENTAL HEAT STORAGE AT THE GRAND COULEE DAM

Fig. 3

loss by conduction and radiation In the case of the experimental storage oven, it was found that the heat loss at 555 degrees was 2.65 kilowatts. Not all of this heat, however, can be charged as loss because if a basement is reasonably tight, any heat liberated into such a basement serves to warm the basement ceiling and therefore, makes for a warm living room floor This adds to the comfort and reduces the amount of heat required in the room above.

These performance curves, as well as the calculations, reveal that the heating elements used are too small to fully charge the oven in ten hours. Also, the "holding" curve and the "cooling" curve reveal that if heat is to be stored more than one day before being used, more insulation should be built into the oven.

PRACTICAL EFFECTIVENESS OF USE OF STORAGE OVEN

In Figure 4 is shown a 24- hour load curve for an Eastern Washington municipality in which some of the cooking is done by electricity, but no electrical heating is used On this curve is superimposed an assumed heating load showing a new peak, approximately 85 per cent above the present peak load By clock control of a large number of heat storage ovens in a given district, the system load could be built up to an approximation of that shown in which the revenue producing load has been increased some 178 per cent without increasing the demand on the system more than 20 per cent above the peak Obviously, the expense of this type of control is borne by the customer, and is not prohibitive for the usual installation.

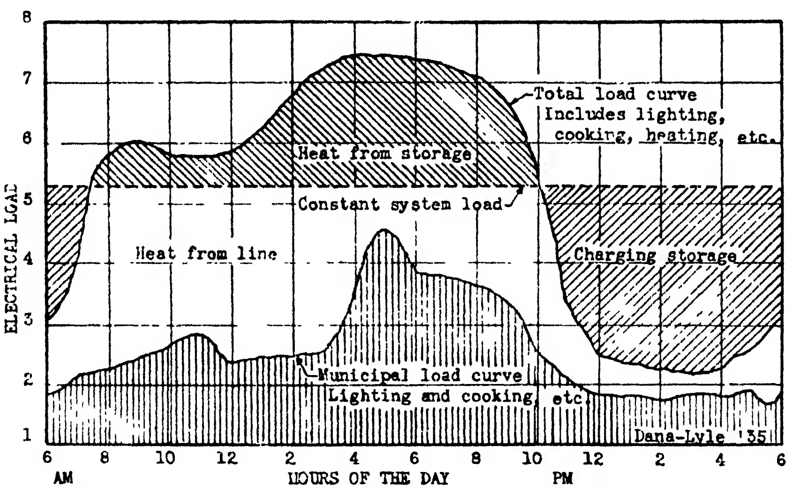


Figure 4 Typical daily load curve for an Eastern Washington Municipality with an assumed heating load added to illustrate the advantage of heat storage

COST OF DOMESTIC HEATING

Annual cost for heating an average six room residence will depend upon the weather, the requirements of the family occupying the residence, and the habits of the individual controlling the furnace However, for purposes of comparison it may be assumed that a stoker-fired furnace would use between 7 and 10 tons of coal per annum

Furthermore, assume that this coal costs $8.50 per ton delivered, and that it has a heat value of 13,000 BTU's per pound.

Experience shows that such a furnace, on the average, will deliver to the rooms as useful heat, only 50 per cent of the heat in the coal.* On this basis, eight tons, costing $68 00, would furnish 104 million BTU's of useful heat during the heating season To furnish the equivalent of this heat electrically would require 30,500 kilowatt hours. If the net cost for this amount of electricity were to equal the net cost of the coal, then the rate for electricity for heating would need to be $0 00223 per kilowatt hour

View of the heat storage oven showing the cold air duct to the inlet Also note the by pass duct passing over the oven. Electrical connections to the heaters are shown entering the cold air inlet.

Tests on a typical home equipped first with a coal stoker, and later with an oil furnace showed that the cost for heating with oil was 88 per cent higher than if it had been heated with a coal stoker[9] Experience seems to show that in many cases this ratio is much higher On an equal basis with oil, the rate for electricity as illustrated above, would need to be $0 00419 per kilowatt hour.

However, there are other factors which enter into the comparative value of electric heat which might justify a somewhat higher rate per kilowatt hour than is cited above in competition with oil. For instance, no coal bin or oil tank is required, and no soot is discharged from the chimney to re-enter the house through doors and windows This fact alone would conceivably require less frequent cleaning and redecorating throughout the house These items are difficult to evaluate, but it is reasonable to assume that, in the eyes of a considerable number of users, the advantage of heating with electricity would justify an increase of perhaps 50 per cent over the calculated rate of $0.00419 cited above, or a rate of $0 00628

In the light of the above analysis, it is interesting to note that the W W P Co. offers a rate of $0.008 for domestic water heating and that under the terms of many old accounts, a rate prevails for water heating as low as $0 00555.

ADVANTAGES OF ELECTRIC HEATING WITH STORAGE

To the power producer, the use of controlled heat storage represents an opportunity.

1 For increased revenue without a proportionate increase in capacity of equipment either at the generating station or in the distributing system

2 For an improved load factor during the heating season and so a reduced relative peak demand on the system

3 For brief interruptions to service without attendant criticism from the consumer

[9] See Engineering Experiment Station Bulletin No 39, "Fuel Economy in Domestic Heating" 1932 by Homer J Dana and Howard H. Langdon

To the power consumer, the use of electrical heat storage results in advantages as follows:

1. Opens the way for a reduced rate for heating energy.
2. Removes the need of space in the basement for a coal bin
3. Removes the necessity for handling coal or ashes.
4. Possesses no tendency to cause dirt or dust to accumulate in the house.
5. Greatly reduces concern as to power service interruptions
6. Permits increased rate of heating such as might be desired for warming up the house in the early morning.

CONCLUSIONS

Although the arrival of warm weather prevented more than just a start on actual working tests on this storage, still enough data were secured to establish the workability of the device

Heat was stored up at night and used to keep the house comfortable during the day As far as the occupants were concerned, there was no apparent difference between this type of heating and heating by the usual hot air furnace No undesirable features disclosed themselves, and all of the problems encountered are clearly subject to satisfactory solution.

Further work remains to be done in working out details of the damper mechanism and other details of control to make it fully automatic Further reduction of heat losses will be studied Determination needs to be made of the optimum size of storage for any given size of house Simplification of controls should be accomplished And further working tests should be made to determine if any destructive effects can be expected from repeated heating and cooling of the storage medium and of the walls of the storage oven Such tests are being planned for the coming winter.

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46 The Feasibility of Using a Heat Storage Device for Domestic Heating with Electricity By Homer J Dana and R F Lyle, June, 1935

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ELECTRIC HOUSE HEATING SERIES, No. 3

Studies of Summer Air Conditioning For Domestic Comfort at Grand Coulee Dam Site

by **Homer J. Dana**

Assistant Director, Engineering Experiment Station

and **R. E. Lyle**

Engineer of Tests at Mason City

Report Sponsored by
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H. V. Carpenter, Director

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits" The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service The last named includes tests and analyses of coal tests and analyses of road materials, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors etc

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SUMMER AIR CONDITIONING TESTS AT MASON CITY

By **Homer J. Dana and R. E. Lyle**

INTRODUCTION

Popular interest in summer air-conditioning has been greatly increased by the extensive use during the past two or three years of air-conditioning equipment in theaters, stores, and very recently in railroad trains. After experiencing the degree of comfort available in these public places, many people are beginning to appreciate the advantages of summer air-conditioning in the home and are seeking to inform themselves regarding details of this latest contribution to human comfort.

When opportunity was given to conduct a series of tests[1] for electrical house heating in the 100% electrified town of Mason City, plans were also made for investigating the possibilities of domestic air-conditioning in the region to be supplied with power from the Grand Coulee Dam when it is completed.

CONCLUSIONS

The summer weather of the Inland Empire region of the Pacific Northwest is characterized by moderately high temperatures and low relative humidity. Therefore, summer air-conditioning as regards domestic application more particularly, does not require particular attention to the removal of moisture in order to assure comfort.

In this region there are about five months of the year during which air cooling is beneficial. During this period, according to computations made from the 1935 weather reports for this area, there would

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[1] Through the courtesy of the Mason Walsh Atkinson-Kier Co., contractors on the Grand Coulee Dam, the State College of Washington was accorded the privilege of using this 100% electrified town as a field laboratory for studying domestic heating with electricity, making tests on thermal building insulations, making tests on methods of heat storage, studying the subject of summer and winter air-conditioning, system electric heating load, demand factor, etc.

Appreciation is hereby expressed to the Washington State Planning Council, and to the Columbia Basin Commission for their valuable assistance in sponsoring these tests.

Special mention is made of the loan of air conditioning equipment for these tests by the Westinghouse Electric & Mfg. Co., and by the General Electric Co. through the James Smyth Plumbing Co. of Spokane. Also the Wesix Co. of San Francisco furnished certain instruments and apparatus used for these studies.

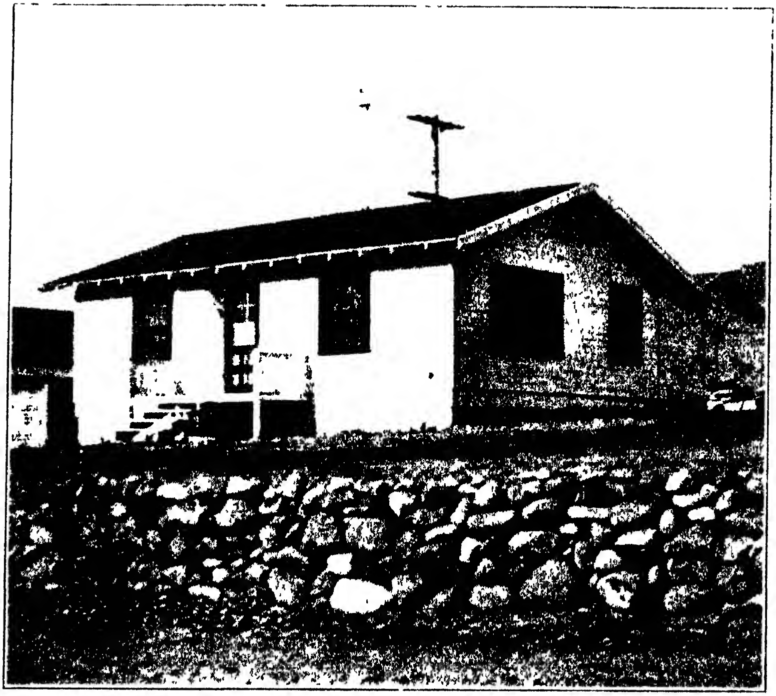

Fig. 1. One of the Type B houses in Mason City which was specially insulated for these tests

be 92 days during which cooling would be required, with a total of at least 594 hours of operation of equipment. This would be equivalent to an average of 6.4 hours of operation per day used.

The power required for small domestic applications of summer air-conditioning equipment would range from one kilowatt upward, depending upon the cooling capacity installed and the air circulating system employed. At the lowest prevailing domestic rate of 2c per kw hr for power in this region, the average cost per day used during the season would be from 13c up.

User-comfort from summer air-conditioning depends very definitely upon proper distribution of cooled air in the room, characterized by an absence of perceptible drafts. Air movement in a warm room may contribute to the comfort of the occupants, but drafts of cooled air cause a feeling of chilliness which defeats the object of air cooling, namely, greater comfort.

OBJECT OF TESTS

It was the purpose of these tests to learn more definitely the extent to which summer air-conditioning would apply in the Inland Empire and its possibilities for becoming of commercial importance in the use of electric power from the Grand Coulee Dam.

Furthermore, since the average home-owner is more or less unacquainted with the principles of summer air-conditioning, this report will explain some of the essential features and give a simple description of the method of providing for this type of domestic comfort.

DISCUSSION OF AIR-CONDITIONING

The air which we breathe and in which we live is too often found to be unsuited for the best living conditions. It is either too hot or too cold; too dry or too moist; or filled with objectionable dusts and odors of various kinds. Conditions favorable to good health require that the air should be held within the range of comfortable temperature, its humidity should lie within certain limits; it should be free from harmful dust particles; and it should be changed often enough to dispose of objectionable odors. All of these conditions apply to year-round air-conditioning. The main difference between summer air-conditioning and winter air-conditioning is that in summer, the air fre-

quently needs to be cooled, instead of being heated, and under certain conditions benefit is derived from reducing its relative humidity instead of increasing it.

HUMAN COMFORT

The temperature range between 68° and 72° F is accepted as being most desirable for year-round comfort in the home. When summer temperatures rise greatly above this value, a measure of discomfort is usually experienced. It is true that some relief can frequently be derived merely by imparting a perceptible movement to the air. This movement tends to remove the enveloping blanket of warm moist air which normally surrounds the individual in warm weather and so promotes evaporation of moisture from the skin, thus taking up heat and causing a pleasant sensation of coolness. But benefit from air movement is very limited, and therefore it is usually desirable to cool the air as well. However, even though the air should be artificially cooled to the optimum living temperature, the desired comfort of the individual is not necessarily assured in every respect. If moisture content of the air is high[2], evaporation from the skin is retarded with a consequent feeling of discomfort which may be evident in a feeling of oppression or in a stickiness of the skin or both. Such a condition is occasionally experienced just preceding a summer storm. The remedy is to remove some of the moisture held in suspension in the air and thus lower its relative humidity.

The human comfort zone of relative humidity lies between 35% and 65%. When higher than 65% and if the temperature at the same time is above 70° F., a feeling of physical discomfort is usually experienced. If the relative humidity is below 35%, rapid drying of the skin and of the mucous membranes of the body takes place. Prolonged exposure to very low relative humidity usually affects the health of

[2] Relative humidity is a term which denotes the amount of moisture actually suspended in the air as vapor as compared to the amount which it could contain in order to be fully saturated at that same temperature. The higher the temperature the more moisture a given amount of air can contain, and vice versa. Thus, a given amount of air at 40° may be fully saturated with evaporated moisture and then has a relative humidity of 100%. If the same air were increased to 70° temperature and no moisture were added it would contain only approximately 34% as much moisture as it is able to hold at that temperature without precipitating. In other words, its relative humidity at 70° would be 34%. Again if the same air at 40° and 100% relative humidity were cooled to 35°, some of the moisture would condense and be precipitated and its relative humidity at the lower temperature would still be 100%. Then if this same air were heated again to 70° without adding any moisture the relative humidity would be approximately 28%.

the individual, often resulting in some type of ailment affecting the nasal passages. Hence, it is important that relative humidity receive its proper consideration in connection with summer air cooling.

In some regions, high relative humidities prevail in summer-time and provision needs to be made for dehumidifying the air. In other regions, the percentage moisture content is normally so low that when the air is properly cooled its relative humidity is automatically brought up to a more healthful level In the Inland Empire, which embraces that part of the State of Washington lying between the Cascade Mountains on the West and the foothills of the Bitter Root Mountains in Idaho on the East, the summer climate is usually characterized by rather low relative humidity. Therefore, the extraction of moisture from the air for summer air cooling in this region does not constitute a major problem, although at times benefit may be derived from this feature also.

AIR COOLING

Summer air cooling can be accomplished by passing air through a spray of cold water, or by passing it over the cooling unit of a mechanical refrigeration plant. Since the usual domestic water supply is either not cold enough, or is not economically available in sufficient quantity, the mechanical refrigeration method of cooling is usually employed.

COOLING EQUIPMENT

Practically all mechanical refrigeration systems for air cooling include three essential units First, the evaporator or cooling unit usually consists of a group of pipe coils inside of which ammonia, sulphur dioxide or some other refrigerant is boiled or evaporated This evaporation occurs at a low temperature and takes up heat, thus serving to cool the air passing over the outside surface of the cooling unit. The cooling unit may be located in the room to be cooled, or it may be located in an air duct system serving one or more rooms

Second, there is the compressor unit which pumps the evaporated ammonia or other refrigerant out of the evaporator coils at low pressure and delivers this gas to the condenser at a higher pressure where it is condensed into liquid ready to be used again in the evaporator

The compressor, driven by a motor, is usually located in the basement although in small installations it may be located in the same room with the evaporator

Third, the condenser unit usually consists of a set of pipe coils into which the gas from the evaporator is pumped by the compressor to be condensed into liquid refrigerant again This condensing process removes the heat from the refrigerant which is absorbed while in the cooling unit The condenser coils may be cooled by air, but more frequently are equipped to be cooled by water flowing over or around them The condenser is usually located near the compressor

These three units—the evaporator, the compressor, and the condenser—are permanently connected together with pipes and valves and their operation is controlled either manually or automatically

When installed permanently in a home, the compressor and condenser units are usually located in the basement with cooling water connections, and waste to the sewer The evaporator, or cooling unit, may also be located in the basement and connected to the ducts of the forced air circulating system; or it may be located in the room to be cooled, and provided with a small circulating fan to increase its effectiveness in cooling Automatic control may include a thermostat in the room to be cooled, which starts and stops the compressor, or controls the circulating fan to the evaporator as required

BUILDING INSULATION

The removal of heat by mechanical refrigeration requires power, the amount depending upon the rate or the size of the "heat load" Obviously then, in the interests of economy, it is desirable to reduce this heat load as much as possible To this end, it is customary to close the doors and windows of an air cooled room, and to provide window shades or awnings against the entrance of direct sunlight

The load which must be handled by air cooling equipment includes heat given off by occupants of the room, the heat, if any, given off by mechanical or electrical equipment in the room, and the heat which may enter from the outside as warm air, or by conduction through the walls and ceiling, or as sunlight through the windows

The transfer of heat through walls and ceilings can never be wholly eliminated, but it can be reduced by the use of heat-insulating

materials[3] These materials include slag or rock wool, expanded mica ore, diatomaceous earth, and vegetable fibre of various kinds. The latter may be in loose form, such as balsam wool, or shredded tree bark, it may be in quilted form, such as dried seaweed sewed between layers of paper, or it may be in compressed board form consisting of wood, straw, or cane fibres.

Use is also being made of the heat-reflecting properties of polished metal foil. This usually comes cemented to a heavy paper which is installed in the walls and ceiling during construction. Sawdust and planer shavings have also been used to fill air spaces in walls and ceiling but are open to several objections. They are subject to excessive settling, they harbor vermin, they are not waterproof, and are considered as increasing the fire hazard.

Tests have been made which show that the investment required to properly insulate the average residence will be returned in the cost of fuel saved within a period of three years.[4] This refers to winter-time saving only. When summer air cooling is added, this same investment does double duty, therefore giving to building insulation a place of first importance in relation to comfort and economy in a home.

DESCRIPTION OF TESTS AT MASON CITY

Two houses in Mason City were equipped for summer air-conditioning tests during 1935. Both were single story structures with low composition roofs and with ventilating louvres in the gables, which were kept open during the summer. The outside walls consist of matched siding, building paper, sheathing, 3½" wall space, and an inside surface of beaverboard or of ½" Inso-board. Ceilings were also of the same material nailed to the joists. Roofs were of ¾" sheathing covered with red slate-faced composition roofing.

In House A, the ceiling and walls were insulated with three inches of "Unifill." Provision was made primarily for cooling the living room, although some benefit was also derived in adjacent rooms. In this house, all the refrigerator equipment was located underneath the floor. Suitable air ducts and a circulating fan were provided to circulate air from the room over the cooling coils and back to the room.

[3] See Eng. Exp. Bulletin No. 45.
[4] U. S. Bureau of Industrial Research.

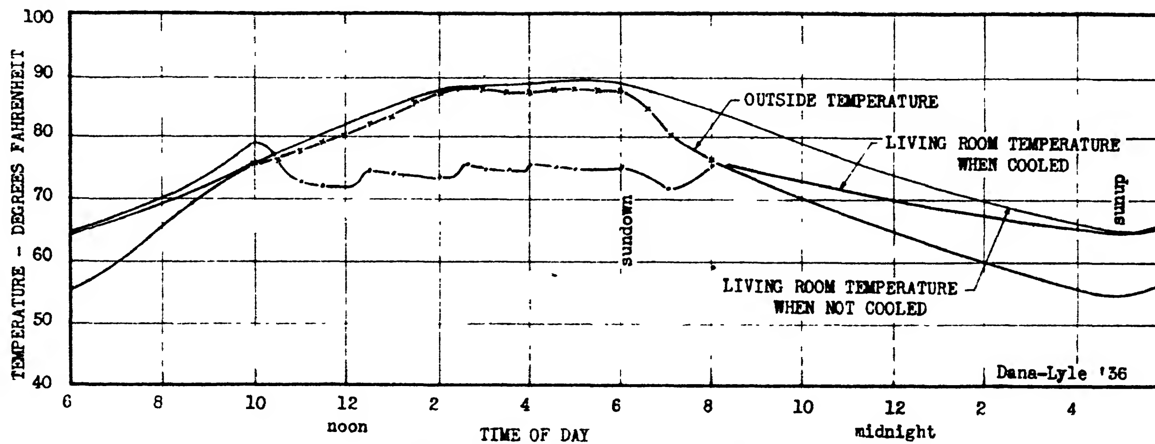

Fig. 2. Temperature control in House B.

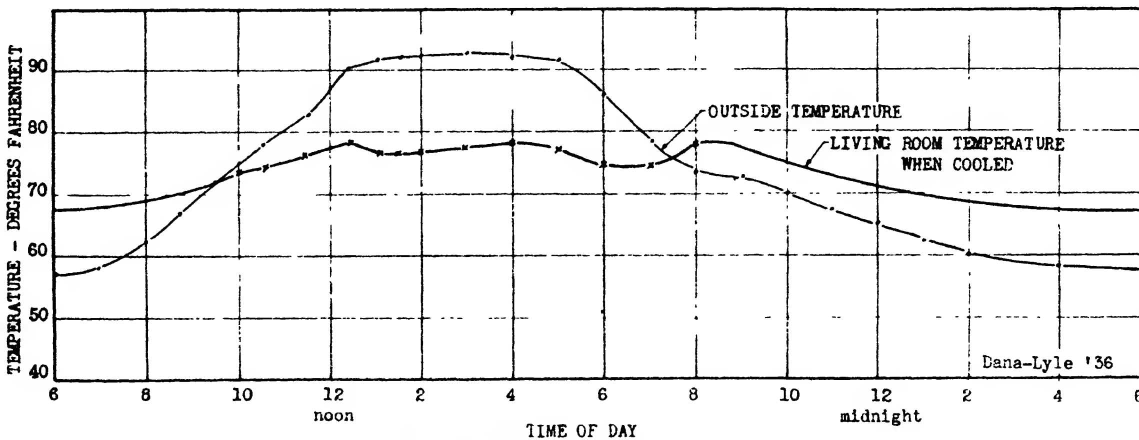

Fig. 3 Temperature control in House A.

House B, although of different shape and dimensions, employed a similar type of construction except that all the air spaces in the walls and between the ceiling joists were filled with mineral slag wool. In this house, the refrigerating equipment consisted of a portable unit including all three refrigerating elements located in the room being cooled. Flexible electrical and water connections enabled the equipment to be transferred from one room to another.

Each installation was more or less typical of the type of equipment commercially available for domestic summer air-conditioning.

THE AIR COOLING SEASON

Figure 2 shows a typical temperature curve for one of the insulated houses when cooled artificially. Subsequent tests showed this installation capable of holding the inside temperature as much as 26 degrees below the outside temperature, but of course such a large temperature difference is not usually expected or advised. In Figure 2 the time of operation of the thermostat is reflected in the room temperature curve.

Figure 3 shows the temperature control afforded by artificial cooling in another house in which the walls and ceilings were insulated. In this case the capacity of the cooling unit very closely approximated the heat load imposed upon it so that there was no need for the thermostatic control to operate.

AIR-CONDITIONING PERIODS

In Figure 4 is shown a graph of the daily maximum and minimum temperatures prevailing in Mason City for the five warmer months of the year. All temperatures above 80° F. indicate periods in which air cooling can be profitably employed for at least part of the day. In Figure 5 is shown the average number of hours per day in which a temperature above 80° F. is to be expected as related to the maximum temperature reached that day.

Table 1, based upon Figure 4 and Figure 5 shows the number of hours per month during 1935 in which air cooling was found desirable.

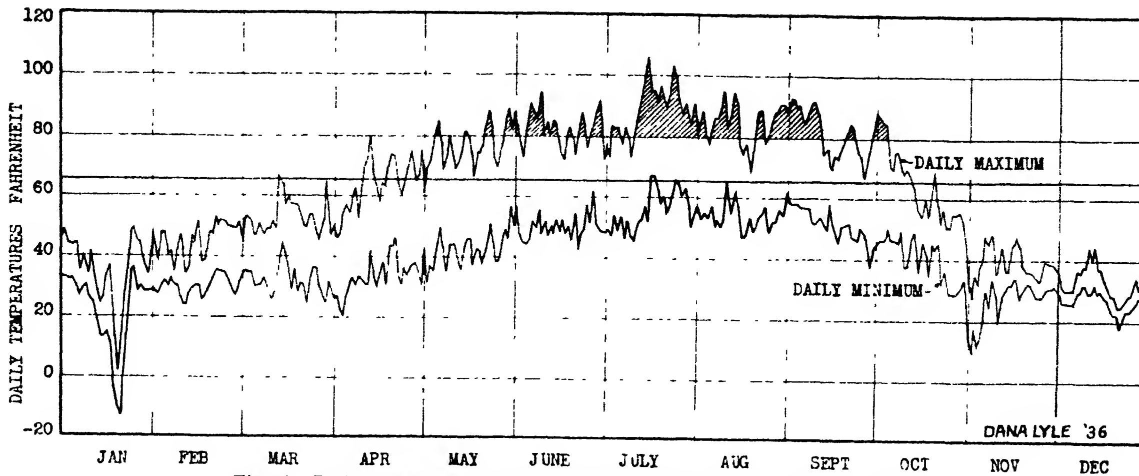

Fig. 4. Daily Maximum-Minimum Temperatures at Mason City for 1935.

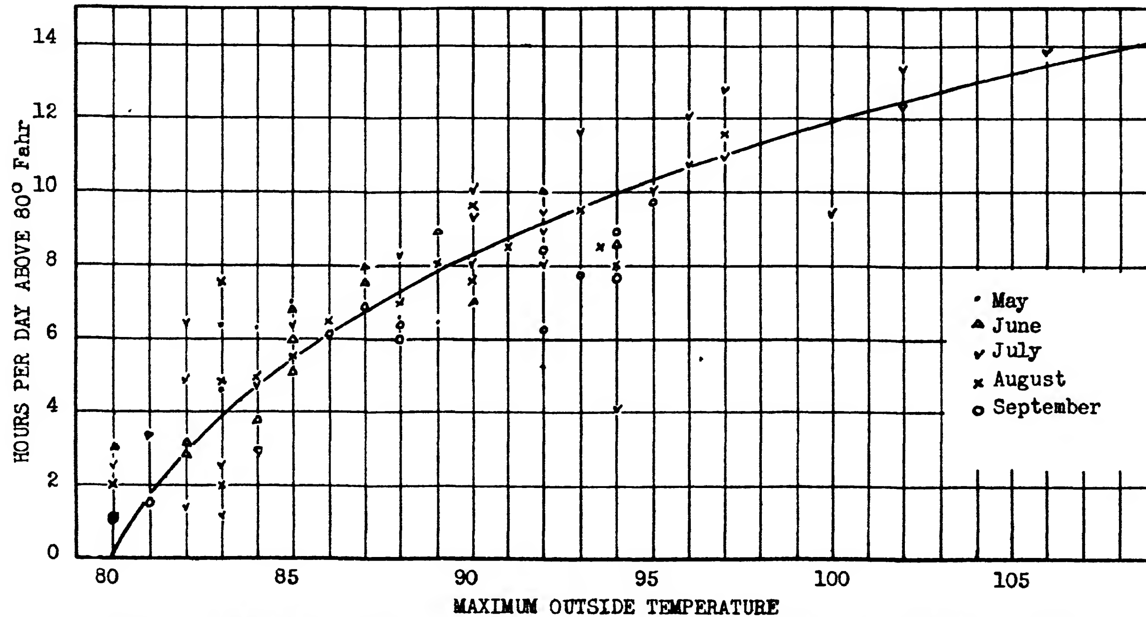

Fig. 5. Illustrating the number of hours per day cooling would be desirable when outside temperatures rise above 80° F. This curve is based upon 1935 temperature records at Mason City.

Table 1.

Month 1935	Days temperature reached 80° F	Total hours above 80° F.
May	10	42
June	15	86
July	27	212
August	22	163
September	18	91
Total	92	594

It is recognized that the area to be served with power from Grand Coulee Dam will not all be subject to temperatures corresponding to those prevailing at Mason City. Some sections will have more and some will have less hours per day when the temperature will be above 80° F and when cooling would be desirable. However, Table 1 may be accepted as being close to the median of the prevailing temperatures in this region.

No temperature records are available for Mason City prior to 1935, but such records are available for certain other points in the Inland Empire. Inspection of such records shows that the summer of 1935 represents an average of the past six years, as regards the number of days during which temperatures exceed 80° F.

On this basis, therefore it may be assumed that Table 1 is representative of the seasonal demand for domestic air cooling in this region.

POWER REQUIRED FOR AIR COOLING

The amount of power required for air cooling depends in general, upon the size of the heat load to be handled. This is affected by size of room, amount of heat leaking into room, heat given off by people and equipment within the room, etc. In order to determine the capacity of the cooling equipment needed and the power required for any given installation careful calculations of all variables must be made. However, for small domestic applications in well insulated homes the power requirements of the two experimental installations for these

tests would probably be representative Table 2 gives the average power requirements derived from data secured in these tests

Table 2.

House	Cu ft cooled	Test hours operated	KW hrs used	Aver power used	KW hrs pr Seas
A	5195	100 95	211 3	2 08 KW	1254 KW hr
B	3552	361 63	341 5	0 94 KW	594 KW hr

From Table 1 it is shown that the expected average annual domestic cooling period in this region will be approximately 600 hours, and from Table 2 the energy used for a typical small domestic application would range from 550 to 1250 K W hrs Table 3 shows the annual cost for power for cooling based upon several hypothetical rates

Table 3.

House	Annual KW hrs used	Annual cost at sample rates per KW hr				
		3c	2c	1c	¾c	½c
A	1250	$37 50	$25 00	$12 50	$9 37	$6 25
B	550	16 50	11 00	5 50	4 12	2 75

For most localities in the Inland Empire there prevails at present a domestic rate for electricity in which the lowest step is 2c per K W hr, and those homes having an electric range usually consume enough electricity each month to get down to the 2c rate On this basis, therefore, the operating cost for a typical domestic cooling system for the summer, on the present rate for power would range from $11 00 to $25 00 spread over a period of five months. It is certain that if power were available for this purpose at a rate as low as 1c per K W hr, a large number of domestic users would find mechanical air cooling very attractive.

AIR COOLING WITH OFF PEAK POWER

It would, of course, be impracticable to cool air at night with off peak power and attempt to store the cold air for use the next day But it would be entirely feasible to cool some other medium such as water, and use it later for room cooling purposes For instance, as-

sume that house A, as indicated in Table 2 uses 2 K W of power for a maximum of 10 hours per day, and that the effective refrigerating capacity of the unit is 1½ tons, or 18,000 B T U per hour[5] Thus, the amount of heat to be extracted from the living room, on the above basis, would be 180,000 B T U per day of 10 hours This represents the amount of heat absorbed by the melting of 1250 lbs of ice

While the economics of using off peak power for domestic summer air cooling has not been investigated thoroughly, it is certain that the idea is mechanically feasible There undoubtedly are certain advantages to this method such as manufacture of ice for other uses, etc

APPENDIX

Moisture Condensed. Provision was made to measure the moisture condensed on the evaporator coils of one of the air cooling installations With outside relative humidities ranging from 19% to 27%, the relative humidities in the room being cooled ranged from 37% to 46%, and the rate of condensation of moisture varied from 5 to 1 07 pints per hour The amount of moisture condensed would depend upon the volume, the temperature, and the relative humidity of the air being cooled as well as upon the temperature of the cooling coils In this case, approximately 300 cu ft of air was being circulated over the evaporator coils per minute

Weather Conditions. During the 48 days on which test data were secured, 37 days were recorded as being clear, with 11 days partly cloudy During that time the wind velocity was recorded as ranging from 3 9 to 13 miles per hour with the majority of the days enjoying breezes at 4 to 6 miles per hour

Cost of Power for Tests. By reason of the special conditions under which the contractors were able to buy power for construction purposes on the Grand Coulee Dam, it was possible to secure power for these tests at 3 mills per K W hr At this rate the summer's operations on house A amounted to $3 76

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[5] A British Thermal Unit of heat is that quantity of heat required to raise the temperature of one pound of water one degree F One ton of refrigeration represents the equivalent cooling accomplished by melting one ton of ice at 32° F

Power Requirements For Air-Conditioning.[6] Table 4 shows the average power requirements for comfort air equipment as installed for domestic use.

Table 4

1	Comfort air-conditioning single room	¾ HP
2	Comfort air-conditioning average six-room house with diversity	3 HP
3	Ditto, but cooling 100% at time, no diversity	5 HP
4	For larger residence with more than six rooms	½ to ¾ HP per rm

Considerable attention was given during these tests to determine the comfort enjoyed by the occupants of the houses in which tests were being conducted It was found that the distribution of the cold air into the room required very careful attention. Perceptible air movement under these conditions seemed to cause a feeling of chilliness which defeated the feeling of comfort ordinarily expected from the reduced temperature It appears to be very important that the air circulation should be at a low velocity, especially in those parts of of the room occupied by individuals at rest.

Since the relative humidity of the air in this region is normally low, there is no great problem involved in dehumidification. The relative humidity of the cool air in the rooms under test appeared to be well within the comfort range and sufficiently low so that the occupants of the room were not aware of other than a comfortable sensation

[6] Will Air Conditioning Become a Desirable Electrical Load, by R E Powers, Elec Jour Nov 1935

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Published by the Engineering Experiment Station
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By Homer J Dana and R E. Lyle, May, 1935.
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By Homer J. Dana and R E. Lyle, June, 1935.
47. Survey of Methods for Heating Fruit-Washing Solutions.
By Homer J Dana, January, 1936
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By Homer J. Dana and R. E. Lyle, February, 1936.

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Methods of Heating Fruit Washing Solutions

by Homer J. Dana

Assistant Director, Engineering Experiment Station

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H. V Carpenter, Director

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METHODS OF HEATING FRUIT WASHING SOLUTIONS

By Homer J. Dana①

INTRODUCTION

The removal of spray residue from fruit has become increasingly important for two reasons: First, the increased number of sprays necessary for controlling the codling moth leaves the fruit at picking time with an exceedingly heavy load of residue. Second, the Federal tolerance on lead and arsenical residue② has been lowered from time to time, thus necessitating more thorough and intensive methods of cleaning. This has led to the development and adoption of double process, or tandem washing, in many districts of the Pacific Northwest and to the use of heated washing solutions.

At first, the heating of washing solutions was employed almost exclusively by the larger growers and by central commercial plants, and in many cases the small grower met the tolerance when necessary, by taking his fruit to these plants. However, there is now a growing tendency among small growers to wash and pack their own fruit, and this has necessitated provision for heating wash solutions cheaply and effectively.③

Commercial types of heaters now available are frequently not within the means of the average grower and consequently many have developed ingenious heaters of their own.

The object of this report is to describe and illustrate the general principles of these devices in order that more growers may become acquainted with methods which are within their means to employ.

① Assistant Director, Engineering Experiment Station, State College of Washington

② The 1935 Federal Tolerance of lead residue is .018 and on arsenical residue is 010 grains per pound of fruit.

③ Appreciation is expressed for the assistance given by Professor F. L. Overley, in charge of Fruit Investigations at Wenatchee, in the preparation of this manuscript, and to Professor Roy E. Marshall, Acting Head of the Department of Horticulture for helpful criticism.

Also, Mr. W. A. Luce, Washing Specialist, State Department of Agriculture, at Wenatchee, greatly assisted in the survey of heating equipment now in use by various growers.

Freqeuntly, one or two ideas are all that a resourceful grower requires to get started. With an understanding of what is required, he will usually be able to adapt some equipment he has on hand, or can acquire cheaply, and thus provide himself with an effective and satisfactory heating system. In those instances where commercial equipment can be afforded, this report will indicate the types in common use from which a selection can be made.

DOUBLE PROCESS WASHING REQUIRED

Tandem washing involves the use of two different cleaning agents, one usually being an acid, and the other an alkali solution, both of which, for best results, should be heated. In some cases, the fresh water rinse is also being heated The dilute acid solution, even when cold, attacks most common metals and when heated, the corrosion progresses very rapidly. Consequently any device intended for heating washing solutions of dilute acid must be designed to operate with a minimum cost for replacement from destruction by corrosion Such heaters may be constructed of expensive monel metal which is not attacked by acid.

CORROSIVE SOLUTIONS USED

On the other hand, the silicate, or alkali solution does not attack metal, but if it is carried through heating coils in the furnace, the silicate deposit quickly chokes up these coils One of the simplest methods of meeting both these objections is to use a steam kettle, or boiler, and conduct the steam through separate pipes into the two solution tanks. Thus, neither solution makes contact with the metal of the steam generator. However, the objection to this method of heating arises from the fact that the addition of the condensed steam to either solution causes undesirable dilution.

If both wash solutions are heated by steam from the same boiler, everything will operate properly so long as the steam temperature is maintained If the fire goes down, steam in the boiler will condense, thus forming a vacuum, which will draw the solutions out of the washer and into the boiler. The silicate solution will do no damage except to form an undesired coating on the inside of the boiler. If the acid solution is drawn into the inside of the boiler, its corrosive action

on the steel will be very rapid, thus causing permanent injury to the boiler. Therefore, it is necessary, as a safeguard, to insert a check valve in the steam pipe to the acid solution, and desirable, though not imperative, to provide a similar valve in the steam line to the silicate tank. Such a valve automatically permits flow of steam away from the boiler but prevents return of the solution to it when the boiler cools off.

SIMPLE STEAM GENERATORS

Figure 1 illustrates a simple heater constructed by mounting two 50-gallon steel drums side by side over a concrete firebox, and piping them together to carry steam to the solution tanks In a plant

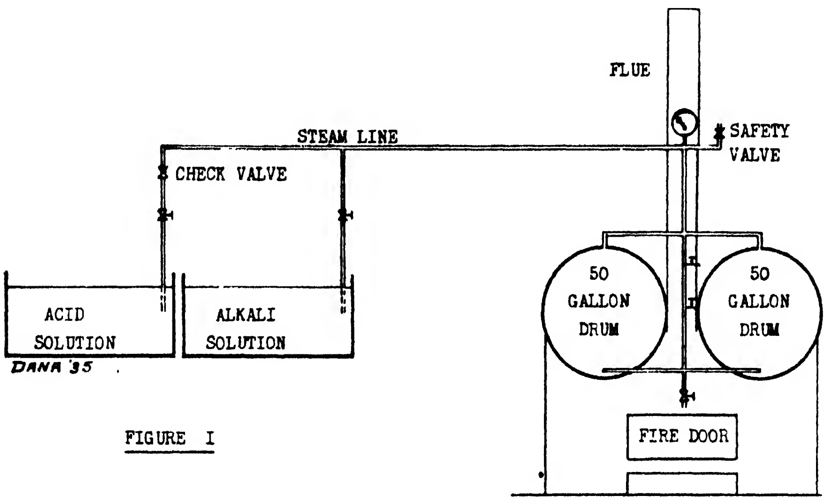


FIGURE I

which packs 500 boxes per day, this type of heater consumes about one cord of slab wood per week. It will be noted that a steam gauge and safety valve are shown. They are highly desirable in an installation of this kind as a guide to proper heat control, and as a means of preventing explosion in case of over firing. It is strongly urged that steam plants, regardless of size or cost, be provided with a safety valve and pressure gauge. It must be kept in mind that any closed vessel which is used in generating steam will blow up if the pressure rises above the strength of the weakest part of the boiler. Provision

of a safety valve on the boiler prevents accidental increase of steam pressure above the setting of the valve.

The use of two drums instead of one increases the water capacity of the boiler thus requiring less frequent filling, Also, as in Figure 1, the heating surface is increased, giving greater steaming capacity.

Water level in the boiler shown in Figure 2 is determined by means of two pet-cocks on the vertical pipe joining the two equalizer pipes between the drums. Filling is accomplished by means of a hose connection to the drain valve. Heat loss may be greatly reduced by covering the top of the drums with dry earth or sand. Figure 2 is a side view of the boiler shown in Figure 1 and gives further details of the pipe connections.

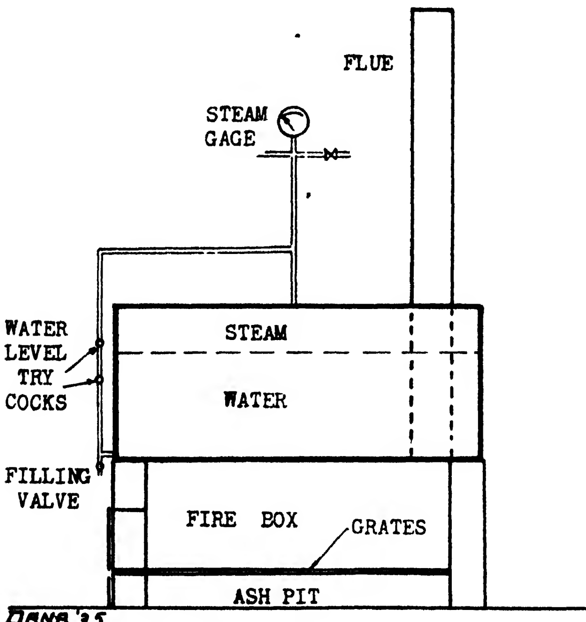
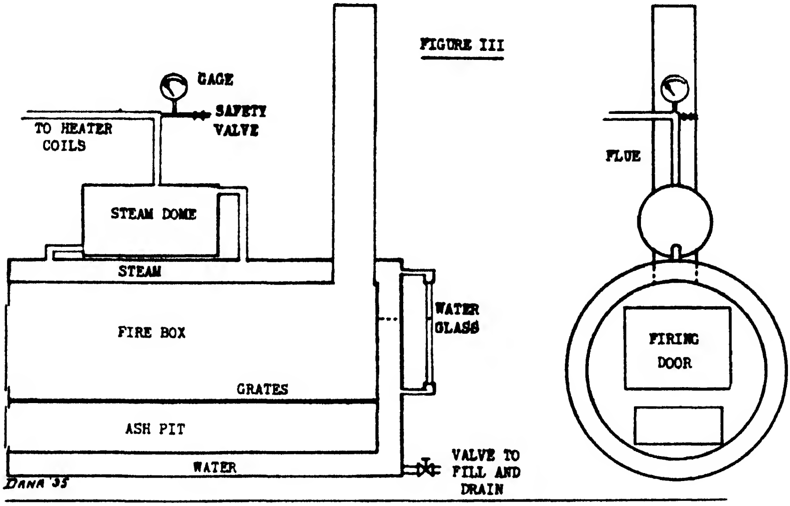


FIGURE II

Figure 3 shows another steam generator improvised from two steel drums of different sizes. The smaller drum is inserted in the larger one and the two are welded together at the open end. A smoke pipe is welded into the other end, and with simple grates and fire

doors, it serves well to supply steam for a small washer. Some users have added a steam dome as shown, which permits a better separation of boiling water from the steam and permits more vigorous firing on that account. It consists of a 15-gallon oil drum connected as shown. A water glass is shown for determining water level, although pet-cocks as in Figure 1 could be used for the same purpose. Heat losses from



the surface can be reduced by applying pipe covering such as asbestos or magnesia. A less effective covering may be made of brick, or dry earth, which is far better than leaving the surface of the boiler exposed.

CIRCULATING COIL HEATERS

As mentioned above, there is some objection to diluting the washing solution with the condensed steam. To meet this objection, some growers choose to circulate the solution through pipe coils in the fire box, and to replace these pipes as often as necessary.

Steel pipe corrodes very rapidly when subjected to the action of a warm acid solution. Copper pipe will last much longer than steel, and monel metal pipe will last indefinitely. Since monel metal is rather expensive it is suggested that thin tubing be used rather than pipe of standard thickness.

Figure 4 shows a heater with pipe coils in the fire box which has been in successful use for more than one season. Two 50-gallon drums were buried with open heads end to end just even with the surface of the ground, and equipped with a fire door at one end and a chimney pipe at the other. Steel bars serve for grates for burning wood Some 20 feet of $1\frac{1}{2}''$ steel pipe was inserted lengthwise inside the drums and over the fire. While this coil did heat the solution, it was stated that 40 feet of coil would have made firing much easier, and would

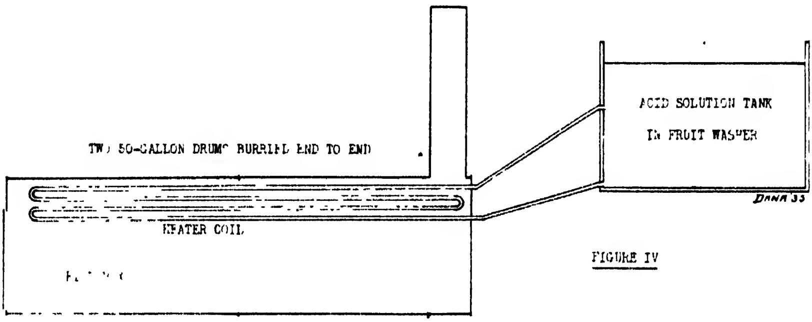


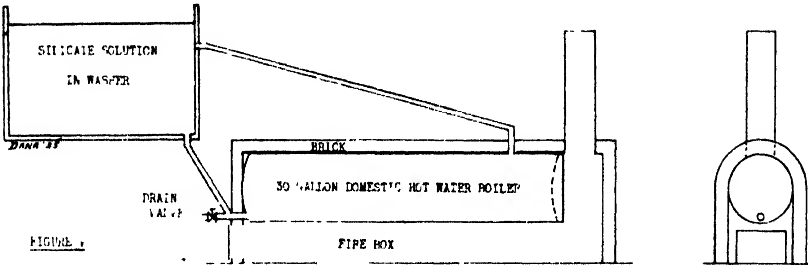
FIGURE IV

have afforded more satisfactory temperature control. Using a 1% acid solution heated to 90° F, this pipe coil has not yet been replaced after practically two seasons' use. With higher temperatures, corrosion would be very much more rapid. Provision should be made for a drain connection at the lowest point of the coil.

It is impractical to use pipe coils in the fire box for heating silicate solutions because the silicate deposit rapidly fills the pipe and stops circulation. This difficulty has been met in part by using a steel drum as the heat exchanger. While the silicate deposit takes place in this drum, there is room enough perhaps for an entire season's deposit without stopping circulation. On the other hand, the presence of this deposit on the inside walls of the heater requires a hotter fire to maintain solution temperatures.

Figure 5 illustrates the adaptation of a 30-gallon domestic hot water tank for heating the silicate solution. It is mounted horizontally over a brick firebox and covered with brick to reduce heat losses. The piping to the solution tank is graded well to promote natural circu-

lation. Heat is generated with a wood fire, and temperature is controlled by adjusting the draft dampers.



FIGURE

LARGE CAPACITY HEATERS

Larger growers requiring heat for one or more washers have resorted to larger heating units Where available, an old tractor boiler makes an excellent steam generator Many such plants are in use. Some are fired with coal, others with wood, some with an oil burner, and some with sawdust Figure 6 illustrates such a plant in which the water level is maintained by means of a float valve connected to control the city water line feeding the boiler This plant burns wood, and operates at about 7 lbs steam pressure It discharges steam into the solution, maintaining the silicate bath in this case at 105° and the acid bath at 110° F This plant was equipped with water glass, try-cocks, safety valve, and whistle.

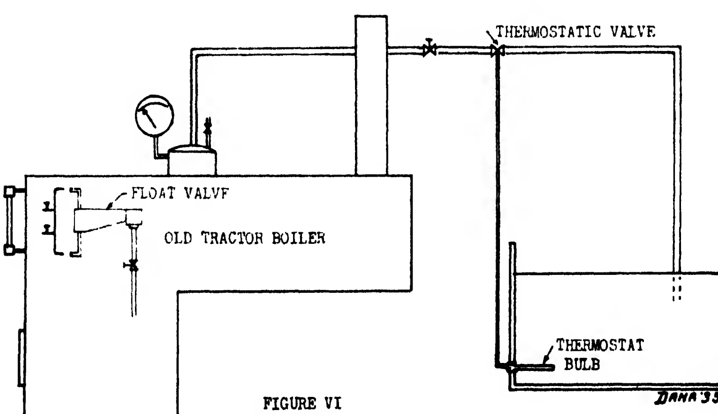


FIGURE VI

Even a domestic steam boiler such as is used for heating a residence is occasionally found doing service in a packing plant. In one instance, such a furnace, using wood for fuel was being used to supply steam to ¾" pipe coils in the solution tanks. Each coil included approximately 20 feet of pipe. The opinion of the operator was that with acid on the outside of the coils, the pipe would last three times as long as if the acid were circulated through the pipe. Both solutions as well as the rinse were heated with steam coils, the condensed steam flowing back through a common pipe to the boiler to be reheated Hand valves controlled the amount of steam to each coil. Advantage of gravity return of the condensate to the boiler was possible by placing the boiler in the basement.

IMPORTANCE OF TEMPERATURE IN WASHING

Hydrochloric acid washing solutions are used in the washing machines at different temperatures varying from the temperature of cold tap water, about 60° F., to 100° F., and sometimes higher. Sodium silicate is not effective as a wash solution at a temperature less than 90° F. The temperatures most generally recommended for sodium silicate are 100° to 110°. However, 120° is often used with sodium silicate on fruit which is hardest to clean.

The higher temperatures may cause injury to fruit if it remains in solution too long. When mineral oil is added to the wash solution, the maximum temperature range may be increased without apparent injury to fruit.

With fruit direct from cold storage rooms and fruit held in orchards late in the season, where the average temperature of the fruit is close to freezing, increased supervision is necessary to maintain temperatures.

AUTOMATIC TEMPERATURE CONTROL

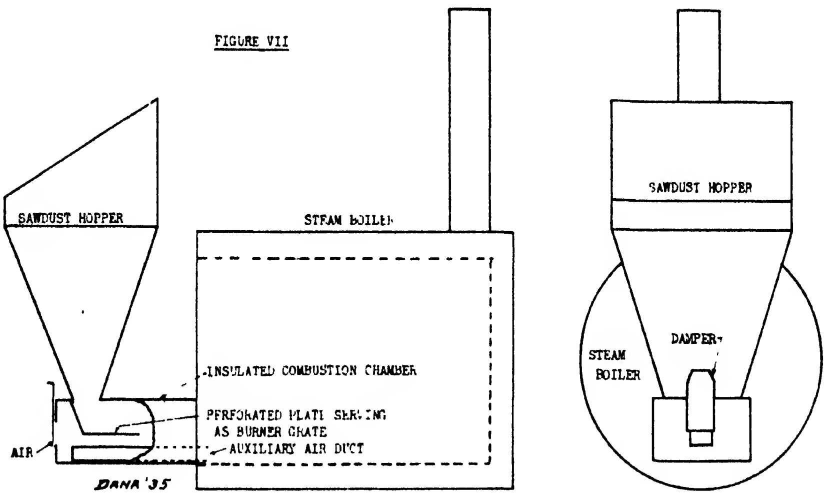
Automatic temperature control is highly desirable to eliminate constant attention required of an operator, and to assure a uniform temperature for best results in cleaning. One type of automatic control makes use of a metal thermometer bulb located in the solution tank and connected by means of a small metal tube to control the opening and closing of a steam valve to the heater. (See Figure 6).

As long as the steam pressure is reasonably constant such a control will serve to maintain uniform temperatures in the bath, and will require only occasional attention from the operator. This type of control can be applied equally well either to steam coils or to steam pipes discharging directly into the solution.

AUTOMATIC SAWDUST BURNER

Where sawdust is available, it affords a cheap fuel for heating. While it may be shoveled into the fire box from time to time, it may also be fed in automatically. Figure 7 shows a common type of automatic sawdust burner with no moving parts. Control is obtained by manipulation of the damper. It is important in all types of heaters that the stack or chimney be tall enough to give plenty of draft. Otherwise heating will be sluggish and not easily controlled.

FIGURE VII



ELECTRIC BAYONET TYPE HEATERS

Considerable use has been made of electric bayonet type heaters for keeping the washing solutions at the desired temperature. These may be controlled by hand switches and are usually turned on and off individually in order to furnish a graduated heat control Caution must be exercised in the use of electric heaters never to turn them on unless covered with solution. If exposed to air they will overheat and burn out in just a few minutes.

AUTOMATIC ELECTRIC CONTROL

Figure 8 shows a group of electric heaters with an automatic temperature control provided. A dial-type thermometer is installed with its extended bulb located in the solution tank. In addition to the usual temperature indicating hand on the dial, adjustable contacts are provided for electric control circuits. A typical circuit diagram is shown, which provides means for automatically turning on one heater

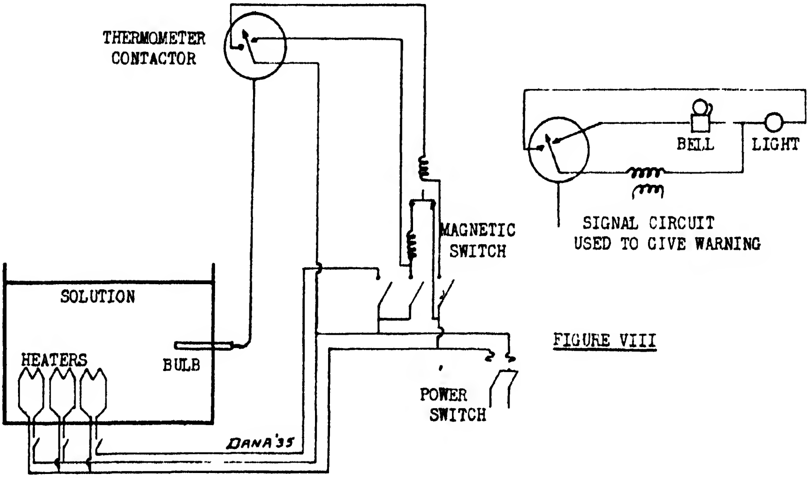


FIGURE VIII

if the solution is too cool and turning it off when the temperature rises to the desired point. Enough heater elements are turned on by hand to almost maintain the desired temperature. Then the automatic control turns on or off an additional heater, as required, thus maintaining the solution temperature with but very little variation from that desired. The circuit diagram shows a magnetic switch and a circuit opening relay associated with a contact-making indicating thermometer.

This same control circuit may also be employed to open or close a magnetic valve in a steam coil, thus affording automatic electric control on a steam heater.

VISUAL AND WARNING SIGNALS

In the absence of automatic control on the heaters themselves, a visual or audible signal may be employed to give warning of the

fact that the temperature is too high or too low. Such a signal circuit is also shown in Figure 8 It employs a bell to indicate temperature too high, and a red light to indicate too cold. As long as the solution temperature remains within the allowable range of two or three degrees, no signal is given.

In the absence of automatic control of the heaters, or of a warning signal as shown, simple dial-type thermometers with extended bulbs may be located where plainly visible to an attendant. Thus, the dumper, for instance can note at a glance and without leaving his work, whether the temperatures are correct or need adjusting. Such thermometers can be provided with copper bulbs for alkali and monel bulbs for acid solutions, and with extended tubing up to ten feet. Five feet long is usually found to be satisfactory

STEAM PRESSURE IMPORTANT IN HEATING

In the foregoing descriptions of steam heaters, it will be noted some boilers were operated at 7 lbs steam pressure and others were operated at 25 lbs, etc Primarily, of course, the strength of the boiler itself determines the highest pressure at which it can be operated safely

What then, are the objects of operating a boiler at a higher steam pressure? The answer is, the higher the pressure at which steam is generated, the more heat it will contain per weight This is a slight advantage in those installations where the steam is condensed into the solution because it requires less weight of steam with consequent less dilution of the solution. Sixteen ounces of water turned into steam at 7 lbs gauge pressure contains 1156 B T U.'s of heat and has a temperature of 230 5° F. The same weight of water evaporated into steam at 25 lbs. pressure contains 1169 B T U's and has a temperature of 267° F, or an advantage of 36° F. In some cases, provision is made for the steam to pass through additional coils in the fire box and thus be superheated An increase in temperature by this means permits the same heating to be done with less stem thus reducing the dilution of the wash solution.

In setting up any heating plant, due regard should be given to the fire hazard involved. Carelessness in this respect jeopardizes the ad-

jacent building and equipment, may result in cancellation of insurance, and if a fire takes place, will cause losses in the handling of the crop far in excess of the cost of taking the necessary simple precautions in the first place.

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ELECTRIC HOUSE HEATING SERIES, No. 4

Characteristics of Heat Storage In Domestic Electric Heating

by **Homer J. Dana**
Assistant Director, Engineering Experiment Station

and R. E. Lyle
Engineer of Tests at Mason City

Report Prepared in Cooperation with
WASHINGTON STATE PLANNING COUNCIL
and
WORKS PROGRESS ADMINISTRATION

ENGINEERING BULLETIN No. 49
ENGINEERING EXPERIMENT STATION
H. V. Carpenter, Director

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

Bulletins available are listed on pages 45, 46 and 47.

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The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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SUMMARY OF HEAT STORAGE INVESTIGATIONS

The practical use of an off-peak heat storage system using rock and brick as the storage material and the hot air principle for heating as observed in a series of tests of an experimental system is presented. The results of these tests show that it is entirely feasible to heat modern homes with this type of heating equipment. Complete air conditioning features are readily adaptable for use as a unit with electrical heating systems of this nature. The operation of such a heat storage system is simple, the controls being automatic.

The principle of off-peak use of power for heating is proven to be entirely practical. Such use will add to the total sale of kwhrs. without increasing the peak demands on the power system and will increase the system load factor during the heating season. The peak demand of an electrically heated house is reduced about 25% when use is made of off-peak storage. The total power consumption is slightly higher than with direct heating, but the overall efficiency can be maintained at a very high level by proper construction and operation. Cheap power from projected hydro-electric developments may make domestic electric heating competitive with the common fuels.

Suggestions are offered as to the design, construction, and operation of rock storage equipment to satisfactorily meet the requirements of modern electrical heating. By the application of accepted principles of heating, a well-insulated and constructed heat storage unit with the proper automatic controlling equipment can be operated to provide efficient and comfortable heating comparable to that furnished by other automatic heating systems, with the combined advantages of direct electrical and hot air heating.

Characteristics of Heat Storage in Domestic Heating

By

Homer J. Dana and R. E. Lyle

INTRODUCTION

The possibility of utilizing hydro-electric power in heating homes, office buildings, factories, etc., during the cold seasons of the year has led in the past to many schemes and experiments for the efficient utilization of such heat. The usual equipment used in residence heating consists of resistance heaters of various types which use power currently with the demand for heat. The power demand on the distribution systems is accordingly very high at certain periods of the day and low at other times. When supplied from a distribution system having a large percentage of residential load, the power demanded by electric heating adds to the peak demand of the other domestic uses, creating a serious situation from the viewpoint of the utilities supplying the load. In addition, electric heating is a critical load to supply since prolonged interruptions to service would be very inconvenient to the customer.

The electric heating load is seasonal in nature with high demands in cold weather and practically no demand in summer. This load has not been attractive to the electric utilities since it means high peak loads as compared to total kwhrs. used. The present sale of electrical power for commercial, industrial, and other uses commands a much greater return than would its use for heating. In order to compete with different types of fuels, the delivered price of the kilowatt-hour must be considerably below the prevailing level.[1] These facts and others have in the past prevented the general use of electric power for house heating.

In recent years it has become apparent that the development of the Grand Coulee and Bonneville projects in the Pacific Northwest might create a surplus of generated power which could be made avail-

[1] See Engineering Experiment Station Bulletin No. 46, "The Feasibility of Using a Heat Storage Device for Domestic Heating With Electricity." July, 1935, by Homer J. Dana and R. E. Lyle.

able for the heating of homes. Because the high peak demand and the low load factor of the heating load aggravate an already bad condition on the distribution system, means have been sought to reduce this peak demand and increase the load factor for the heating load. This can be accomplished by generating heat in a storage compartment in the house during the hours when other demands on the system are at a minimum, and using this heat as needed during the daytime. The power demand during this off-peak period can be somewhat lower than is the maximum demand needed to heat up a cold house The use of power during the off-peak hours tends to fill up the depressions and avoids the peaks of the distribution system load curve, thus making generation and distribution more economical

The storage of heat by accumulation in pea gravel, brick, iron, and especially in insulated tanks of water has been tried in the past,[2] but the cost of electricity has prevented its acceptance. With cheaper power available this method of heating will command renewed interest. As a means of effecting a low cost heat storage installation, the use of boulders as a storage material was studied in the tests described herein The specific heat of stone (0.19 to 0.21) is lower than that of water, but this is offset by the higher density (2 6 to 2.8) and the higher permissible operating temperatures, (water, 100°-240° F. and rock 165°-500° F.). Furthermore, stone for heat storage does not require an expensive steel container as does water.

When heat is generated by electrical resistance units in an insulated compartment filled with rocks and small boulders, the rise in temperature of this material represents stored heat When a motor-operated fan draws air through the heated rocks in the storage compartment, the resulting hot air may be distributed to the rooms of the house through conventional hot air ducts. By use of suitable automatic controls, a home may be heated with a degree of comfort equal to that derived from an automatic oil, gas, or coal furnace installation, and with greater cleanliness and convenience. Such an installation requires a minimum of personal attention.

[2] See Bibliography of Electrical Heating References in Engineering Experiment Station Bulletin No. 45, "Comparative Heat Loss Tests on Insulated and Un-insulated Buildings in the Electrified Mason City at Grand Coulee Dam Site." May, 1935, by Homer J. Dana and R. E. Lyle.

OBJECT OF TESTS AT MASON CITY

A remarkable opportunity for investigating and testing the practicability of electrical house heating was presented when the Mason-Walsh-Atkinson-Kier Company, contractors for the construction of the Grand Coulee Dam, decided to completely electrify their construction camp even to providing electrical heat in the houses. Accordingly, their permission was obtained to conduct a series of investigations of the practical use of electrical heating and air conditioning.[3] To facilitate these tests, a three-room residence designated as a laboratory house for these investigations was erected by the M.W.A.K. Company on a special foundation providing a full basement which was the only departure from the pier type of foundation used under all other houses in the camp.

In the basement of the laboratory house an experimental heat storage unit filled with granite boulders was installed and a series of tests was made during the winters of 1934-35 and 1935-36 to determine its feasibility. A first progress report on the feasibility of such a heat storage unit[1] was published by the State College of Washington in July, 1935. This report is based on a second year's study in Mason City.

SCOPE OF TESTS

If an extensive electrical heating load is to be applied to a distribution system, careful attention must be given to securing satisfactory coordination of this low revenue load with the higher paying commercial and industrial loads. This is necessary in order that the heating load may be added without jeopardizing the existing revenue. The opportunity to study the load characteristics of a large number of electrically heated homes in Mason City, Washington, furnished a large amount of information on the peculiar characteristics of the domestic heating load The variation of consumption of individual houses with weather conditions, the range of consumption among different families, the maximum demands for power placed on the system, the diversity of demand of groups of houses, and a number

[3] The Mason-Walsh-Atkison-Kier Company not only granted permission to the State College of Washington to use Mason City, the largest laboratory of its kind in the world for these studies, but they also assisted in every way possible by loaning materials and equipment needed This assistance is greatly appreciated because the studies would not otherwise have been possible.

of other factors bearing on the problems of power distribution for the heating load were also available to be studied. Observations at first hand of the heating comfort derived in the home from electric heat and comparisons of the operation and results obtained from heating equipment of different types were made. At the same time the necessity of proper building construction and insulation in conserving heat was demonstrated.[4]

HEAT STORAGE TO USE OFF-PEAK POWER FOR HEATING

The average domestic heating customer expects to be supplied with heat at a high rate in the mornings for heating up his cold house and at a lower rate during the balance of the day, as the weather and occupancy dictate The combined load curve of a group of heating customers corresponds roughly to the variation of outside temperature, since the heating load is much larger than the domestic load. Morning and evening peaks and a minimum demand during the middle of the day and at night are notable features. If heating is by the direct method, the peak demands will occur at about the same hours as the maximum demands from other domestic uses, and thus will require a corresponding increase in the load carrying capacity of the electrical distribution system. That is, the power system would have its peak loads greatly increased, usually without a proportionate increase in average load.

To offset this condition, use can be made of off-peak power in heat storage units to level the load curve, increase system load factor, and improve distribution conditions. This use carries possibilities of increased revenue and load factor for power systems without raising the peak demand.

The practical operation of an experimental rock heat storage system[1] at Mason City was observed during a period of varying outside temperature and weather conditions to determine its feasibility as a practical house heating plant, it energy consumption, its thermal efficiency, and its adaptability for overcoming the economic restrictions which have thus far limited the use of electrical energy for space heating.

[4] See Engineering Experiment Station Bulletin No. 45, "Comparative Heat Loss Tests on Insulated and Un-insulated Buildings in the Electrified Mason City at Grand Coulee Dam Site," May, 1935, by Homer J. Dana and R. E. Lyle.

CONSTRUCTION OF EXPERIMENTAL HEAT STORAGE UNIT

A two days' supply of heat for the three-room laboratory house was determined by calculation to be about one million B.T.U.'s. To store this amount of heat at a reasonable temperature a mass of stone and brick 4½ x 4½ x 5½ feet was required. The storage unit as erected in Mason City consisted of a four-inch shell of common brick laid up with clay, inside of which were piled granite rocks and small boulders found close at hand. An insulating layer of three inches of Mineral Wool and an outside course of hollow tile completed the walls and top of the storage unit.

The electric heater elements in the storage unit were controlled by a time switch, the charging rate being selected by means of hand-operated switches. Rates of 10, 7.5, 5.2 and 3 kw. could be used at will. The heater elements were made up of spirally wound chrome-molybdenum resistance wire[5] supported by porcelain insulators on an iron framework. Each of two frames supported a 2.5 and a 3 kw. 220 volt element. These frames were inserted in the bottom of the furnace through the cold air entrance. A carefully standardized watt-hour meter was used to measure the kwhrs. of heat energy introduced into the storage chamber.

Provision was made for bringing cold air from the rooms into the storage unit at the bottom of one end and removing the heated air at the top of the opposite end after the fashion of hot air furnaces. Longitudinal spaces were provided in the bottom at the cold air entrance and in the top at the hot air exit to equalize the flow of air through the oven. A thermostat, inserted through the side of the storage unit, was connected to interrupt the charging current when the maximum temperature was reached. Hand-operated dampers in the by-pass and hot air ducts controlled the mixing of the cold air from the rooms with the very hot air from the storage unit to reduce the air temperature to a customary value for introduction into the rooms.

An automatic damper control mechanism was so designed that the temperature of the air stream delivered to the rooms would be con-

[5] The Wesix Electric Heater Company, 300 First Street, San Francisco, California, furnished heater coils, control relays, time switches, thermometers, and a set of four radiant-convection type static heaters for use in these tests.

trolled below a limiting level. Because of the arrangement of the air passages in the storage unit, it was necessary to close the damper in the hot air exit whenever the fan was idle in order to secure better control of the flow of heat to the rooms. A mechanical switch was arranged to open this damper mechanism when the fan motor was turned on by the room thermostat.

The tempered hot air from the storage unit was forced into the rooms through a conventional duct system by a ventilating fan[6] which was provided with a cone pulley so that different air velocities could be obtained. Hot air registers were located in the baseboards and cold air was drawn from cold air grilles in the floor of each room.[1] The operation of the motor-driven fan was controlled by a time switch and by a room thermostat. Another thermostat mounted in the hot air duct and connected in the fan motor circuit served to shut down the fan in case that, for any reason, the temperature of air passing through the duct should rise above a desired value.

A potentiometer and calibrated thermocouples were used to measure temperatures at various points in the storage oven. Two thermocouples in the center of the oven and one at the inner brick surface were used to indicate the amount of heat stored, and two others located at the outer surface of the first layer of insulation were used to indicate the heat loss from the storage oven Other thermocouples measured the temperature of the air at different points in the system

STORING HEAT IN THE STORAGE UNIT

Heat generated in the heating elements is distributed mainly by air convection to the individual rocks and is absorbed by conduction in the thermal capacity of the storage material. The volume of air contained within the storage compartment is circulated by natural convection from the heater elements up through the center of the pile of rocks, returning down the sides. The space adjacent to the heating elements becomes very hot and the center of the pile, which receives the current of heated air first, is heated to a higher temperature than the parts next to the walls. Also, the upper portions of the storage space are maintained at a higher temperature than the balance

[6] Brandt Bros., Heating and Ventilating Engineers of Spokane, Washington, contributed the use of a Buffalo multivane type fan for these tests.

of the pile, with the result that the upper part of the compartment stores more heat than the lower part.

Although the temperature was not uniform throughout the storage compartment, (see Fig. 1) it was found that thermocouples placed at selected points within the compartment gave a fairly reliable indication of the amount of heat stored. During the charging period, these thermocouples, being surrounded by air, indicated temperatures somewhat above the actual temperature of the rocks; while during discharge periods the opposite was true. When due allowance was made for this variation, this method of determining the amount of heat charge was found to be satisfactory.

IMPORTANCE OF INSULATING THE STORAGE UNIT

The heat escaping from a storage unit is an important factor in determining the operating efficiency of the heating system. During cold weather, most of this heat escaping into the basement is useful in warming the floors above, but during mild weather it not only constitutes a waste, but may seriously interfere with proper control of the room temperatures.

With dampers carefully fitted in the closed position in order to avoid heat losses through the ducts because of circulation induced by "stack action," tests were made to determine the normal losses through the walls of the storage unit. Preliminary tests were run on the storage unit with three inches of Mineral Wool as insulation. Then four inches of Unifill was applied outside the tile enclosure and the tests were repeated.

In Table 1 are shown the results of these tests indicating the value of the added insulation in reducing radiation losses from the storage unit. The loss by "stack action" through the ducts represents a considerable part of the total loss.

TEMPERATURES DURING THE OPERATING CYCLE

In Figure 1 are shown the temperature variations at various points in the storage unit during three cycles of daily operation when the daily use of heat nearly balanced the input. Temperatures in the walls and top are seen to remain fairly constant, while temperatures in the center of the pile vary with the progress of the heating cycle. Figure 2 shows the charging part of the cycle prolonged until temperatures

Table 1.

Heat Loss From Experimental Heat Storage Unit

Date	Storage Tem °F	Stored Kwhrs	Kw. Input	Watts/ Deg F	Kw loss at 500° F	% of total heat lost per hr at 500° F.	% of Eff. heat lost per hr. at 500° F.
Original Construction—Dampers closed:							
March 9, 1935	380	229	2 97	9 58	4.12	1 29	1.66
Original Construction—Ducts plugged—Radiation loss:							
March 22, 1935	515	329	2.83	6 36	2.74	.86	1.10
Additional insulation—Dampers closed: (See Fig. 2)							
March 2, 1936	465	293	2.55	6 55	2.78	.87	1.12
Additional insulation—Dampers open: (See Fig 2)							
March 5, 1936	420	259	2.55	7.29	3.13	.98	1.26
Minimum useful storage at 165° F = 70 kwhrs							
Useful storage at 500° F. = 248 kwhrs							

Duct loss $= 9.58 - 6.36 = 3.22$ watts/deg F, or $100 \times \frac{3.22}{6.36} = 50.6\%$ of original, or $100 \times \frac{3.22}{6.55 - 3.22} = 96.7\%$ of final radiation loss.

Savings due to additional insulation $= 9.58 - 6.55 = 3.03$ watts/deg F or $100 \times \frac{3.03}{9.58} = 31.6\%$ of original or 46.4% of final total loss.

Loss due to open dampers $= 7.29 - 6.55 = .74$ watts/deg. F., or $100 \times \frac{.74}{6.55} = 11.3\%$ of final closed loss.

Decrease of radiation loss $= 6.36 - 3.03 = 3.33$ watts/deg F, or $100 \times \frac{3.33}{6.36} = 52.4\%$ of original radiation loss.

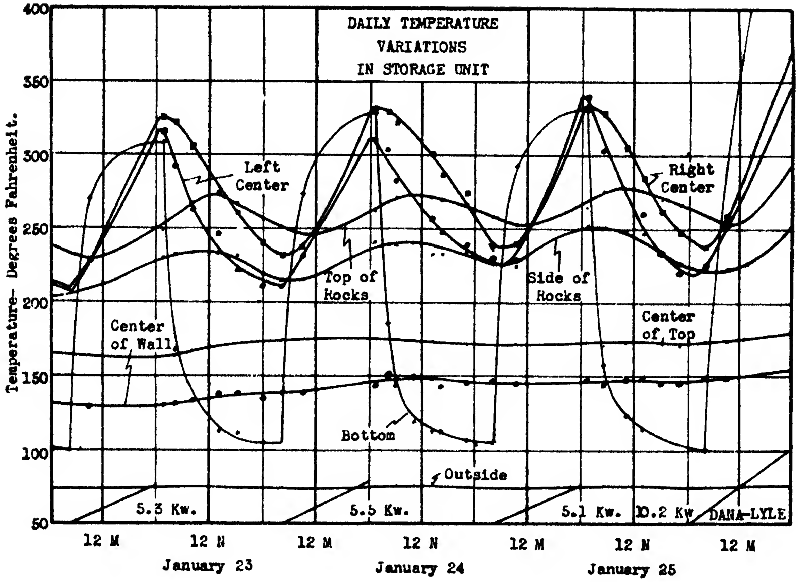

Fig. 1 Daily variation of temperature in experimental heat storage unit in use during average winter weather

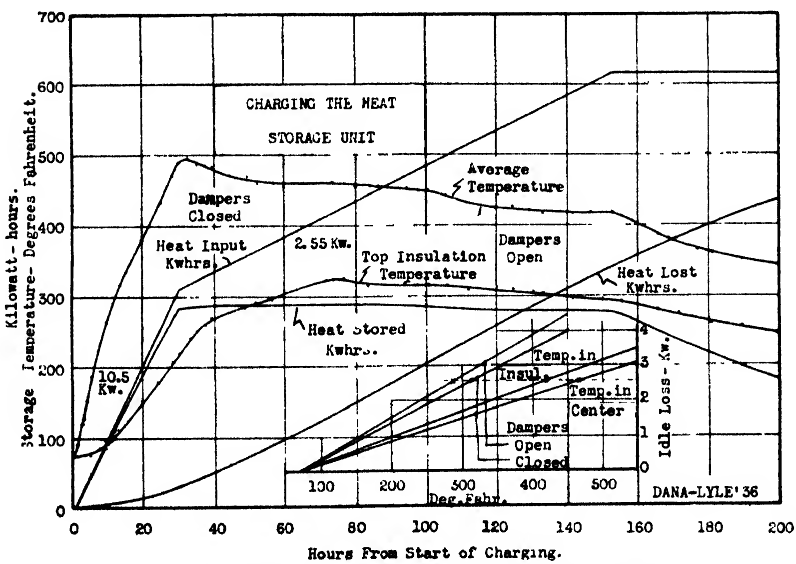

Fig. 2. Showing the building up of the initial charge of stored heat, the radiation losses, and the heat capacity of the experimental storage unit.

became approximately stable. When this condition obtains, the losses are equal to the heat input which can be accurately measured.

DAILY HEAT DEMANDS ON THE HEAT STORAGE UNIT

In evaluating the performance of this experimental heat storage system, it was necessary to estimate at regular intervals during the daily cycle the amount of heat remaining in storage. The heat stored at 6 a.m., 12 n., 8 p.m., and 12 m. was estimated from the temperatures recorded and coordinated with the kwhrs. charged in, the estimated losses, and the heat removed. As mentioned previously, the average of temperatures measured at the selected points in the storage material probably does not represent the average temperature in the storage compartment throughout the heating-cooling cycle. However, the average of temperatures measured at 12 n., when the conditions were more likely to remain steady, probably were fairly close to the true value. From the charging curves of Figure 2 and from calculations of the heat storage capacity of the weights of rock and brick used, the heat stored at 12 noon of each day was estimated and coordinated with the heat charged in and the heat removed to estimate the performance of the heat storage unit.

In Figure 3 are shown the estimated quantities of heat stored at 12 n. of each day's test. Since the stream of air issuing into the mixing chamber is always 50° to 70° lower in temperature than the storage material, there is a minimum temperature at which the rate of heat transfer to the air becomes inadequate to successfully heat the rooms. This minimum temperature is about 165° F. so that, in the test unit employed, a minimum charge of about 70 kwhrs, had to be accumulated before stored heat could be satisfactorily furnished to the house. From the data shown in Figure 2, the idle losses at various storage and temperature levels are estimated in Figure 3. At the minimum useful storage level, the idle loss from the storage compartment was about .55 kw. During mild weather, this alone would be sufficient to heat the test house comfortably.[2]

HOUSE HEATING TESTS WITH THE STORAGE SYSTEM

An extended period of practical operation of this heat storage system was begun on January 15, 1936, and a long continued cold

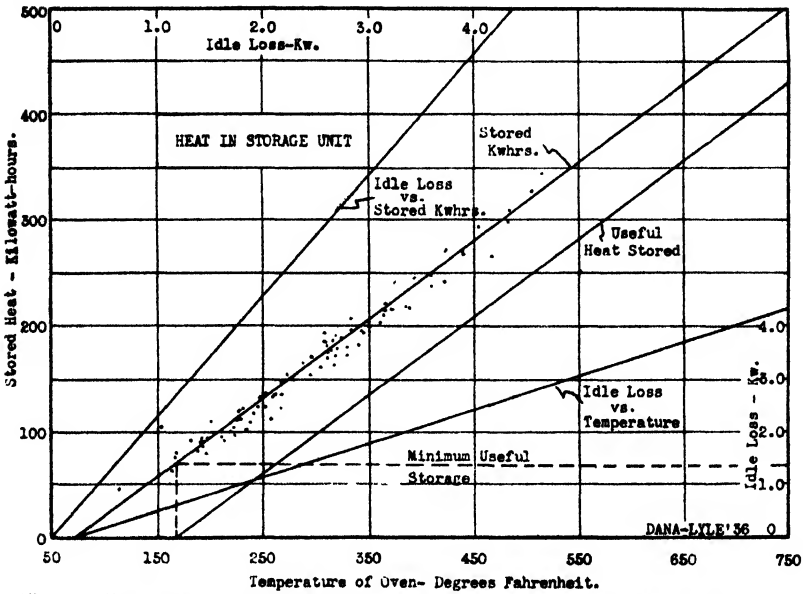

Fig. 3. Shows the quantity of heat stored and radiation losses of experimental heat storage unit at various storage temperature levels.

snap in February offered an excellent opportunity for testing the system under severe weather conditions. Two very cold periods were experienced on February 7-9 and February 13-19, the minimum temperatures dropping to around -8° to -15° F. The mean temperatures during the period occurred conveniently to arrange the daily tests in three groups of progressively colder days. These periods are representative of mild, normal, and severe winter weather in the Pacific Northwest. A fourth period in March was representative of the late fall and early spring days.

In conducting the house heating tests, a uniform schedule of operations was adopted to conform to the usual domestic heating program followed in houses equipped for automatic control of the heating plant. The fan, under control of a time switch and room thermostat, was started heating up the house at 5 to 7 a.m., and was turned off at 10 to 12 p.m. daily. In most of the tests, the storage system assumed the full burden of heating up the cold house in the mornings, but was assisted during the day by heat from an auxiliary unit heater in the basement and from domestic operations. The fan, after being started

by the time switch, operated continuously until interrupted by the room thermostat when the rooms came up to temperature. During the day, room temperatures were maintained at a fairly constant level by the room thermostat. The storage oven was recharged during a 10-hour assumed off-peak period from 8 p.m. to 6 a.m. under control of a time switch and the oven thermostat. During the period February 9-20, the room thermostat was "set back" to 60° F. from 10 p.m. to 5 a.m. and the system operated continuously under control of the room thermostat, following the practice used in many furnace-heated homes with automatic control.

Readings of the house service meter to ascertain the total kwhrs. used in the house and of a meter measuring the kwhrs. introduced into the storage oven were recorded each day. Another watt-hour meter was connected to measure the energy used by the fan motor Several times during each day and particularly at 8 p.m., before the oven heaters were turned on, and at 6 a.m., before the fan was turned on, readings of the oven thermocouple indications were recorded. A recording voltmeter was used to make a continuous record of the heater and fan operation, recording the time during which energy was introduced to the storage heaters and the time the fan motor was in operation. During the heating-up periods in the mornings and at intervals during the day the indications of several glass thermometers hung in the rooms were recorded A recording thermometer placed at an inside wall of the living room provided a continuous record of the room temperatures. A recording humidigraph was used to record the room humidity.

During the period of the tests, the basement was utilized as a laboratory, workshop, and office. Although the basement was well built with air leakage at a minimum, it was necessary to use a 3 kw unit type heater to provide heat in addition to the losses from the storage unit to maintain a temperature of 65° to 70° F A large part of this heat as well as the heat escaping from the storage unit was useful in warming the floors of the rooms above. This heat rising through the floor contributed to the total heat used in the house during each day and, of course, reduced the demand on the heat storage unit by a proportionate amount.

To obtain as much data as possible within the limited time available for the tests, the storage unit was operated at random at various

internal temperatures ranging from 165° to 570° F., the level being determined more or less by the heat demand during the previous day and the charging rate employed The storage heaters were operated about 10 hours during the very cold weather and 8 hours or less during mild weather. Charging rates of 10, 7.5, 5.2, and 3 kw. were used as desired, but occasionally, in order to reduce the temperature level, the storage unit was not recharged during the night. At times, however, it was necessary to use a higher charging rate for a day or two in order to raise the temperature level when the weather was very severe or when the storage level approached the useful minimum.

In tables 2, 3, 4, and 5 are summarized the heat consumption data obtained from these tests. Since electrical energy was used entirely, it is convenient to use the kwhr, which is equivalent to 3415 B T.U.'s per hour, as the unit in speaking of quantities of heat Because the various meter readings were taken faithfully at noon of each day, and only occasionally at midnight, these data embrace the period from noon to noon of each day. An estimate of the percentage of the total effective heat derived from domestic uses, stored heat, and demand heat from unit heaters is shown during weather of increasing severity Domestic consumption was estimated from tests made on several special test houses. Practically all of the kwhrs used for domestic purposes appeared in the house as useful heat, with the exception of part of the heat in hot water which escaped down the drain. In addition, there was a contribution of about 150 watts from each person in the room, which was not taken into account The total amount of heat used per day is generally considered to be proportional to the mean temperature deficiency from 65° F during the 24-hour period, or to the degree-days per day [7] The index "kilowatt hours per degree-day" was fairly uniform during each period and slightly lower for cold weather because the basement was inadequately heated.

The estimated total heat utilized in the test house each day is shown in Figure 4. During the cold weather, the basement was partially heated by a small fan type unit heater to maintain comfortable working conditions, and the bathroom was heated at times during the night by a small static type heater. Consequently, at such times, all of the heating requirements of the house were not furnished from the

[7] The degree-day is a term in common use in heating practice to indicate the deficiency of the mean daily temperature from an average room temperature of 65° F

Table 2.
Daily Heat Consumption of Test House During Early Spring Weather.

	March, 1936										
Date	11	12	13	14	15	16	17	18	19	20	Av.
Mean Temperature Def. from 65°F.	21.5	23	19.5	23.5	29	17	15	23	18.5	20.5	21
Total energy Consumption—Kwhrs.	73	30	35	76	81	90	68	77	79	74	—
Energy to Storage—Kwhrs.	45	0	0	41	44	61	40	49	46	43	—
Charging Time—Hrs.	8.0	0	0	7.0	8.0	7.8	5.25	6.4	6.17	5.75	—
Charging Rate—Kw.	5.62	0	0	5.8	5.5	7.8	7.6	7.7	7.45	7.5	—
Domestic and Unit Heater—Kwhrs.	28	30	35	35	37	29	28	28	33	31	31.4
Effective Heat in Domestic—Kwhrs.	24	24	28	31	32	23	23	23	27	28	26.3
Heat from Unit Heaters—Kwhrs.	0	0	0	0	0	0	0	0	0	0	0
Heat from Storage—Kwhrs.	47.2	50.8	33.8	39.9	52.4	34.8	37.1	50.6	39.9	38.0	42.5
Total Heat Used in House—Kwhrs.	71.2	74.8	61.8	70.9	84.4	57.8	60.1	73.6	66.9	66.0	68.7
Kwhrs. per Degree Deficiency	3.21	3.25	3.17	3.02	2.90	3.40	4.00	3.20	3.61	3.21	3.27
Domestic Heat—Per cent	33.7	32.1	45.3	42.3	37.9	39.8	38.3	31.2	40.3	42.4	38.3
Auxiliary Heat—Per cent	0	0	0	0	0	0	0	0	0	0	0
Storage Heat—Per cent	66.3	67.9	54.7	57.3	62.1	60.2	61.7	68.8	59.7	57.6	61.7

Table 3.

Daily Heat Consumption of Test House During Mild Winter Weather.

	January, 1936										
Date	18	19	20	21	22	23	24	25	26	27	Av.
Mean Temperature Def. from 65°F.	37	35.5	32.5	35.5	37.5	33.5	32	37.5	39	39.5	36
Total energy Consumption—Kwhrs.	59	69	100	139	131	124	126	122	173	126	—
Energy to Storage—Kwhrs.	0	0	29.0	62.5	52 5	52.0	53.0	50.5	102.5	54.0	—
Charging Time—Hrs.	0	0	10	12	10	10	10	10	10	10	—
Charging Rate—Kw.	0	0	2.9	5.21	5.25	5.20	5.30	5.05	10.25	5.40	—
Domestic and Unit Heater—Kwhrs	59.0	69.0	71.0	76 5	78.5	72.0	73.0	71.5	70.5	72.0	71.3
Effective Heat in Domestic—Kwhrs.	27	29.0	27.0	30.0	29.0	27.0	26.0	27.0	26.0	26.0	27.4
Heat from Unit Heaters—Kwhrs.	26	36.0	38.0	43.0	45.5	39.0	40.0	38.5	37.5	39.0	38.2
Heat from Storage—Kwhrs.	68.7	44.7	40.5	35.5	41.4	43.3	42.8	55.0	63.4	65.5	50.1
Total Heat Used in House—Kwhrs.	121.7	109.7	105.5	109.0	115.9	109 3	108.8	120.5	126.9	130.5	115.7
Kwhrs. per Degree Deficiency	3.29	3.09	3.25	3.07	3.09	3.27	3.40	3 22	3.25	3.31	3.22
Domestic Heat—Per cent	22.2	26 5	25.6	27.6	25.0	24.7	23.8	22.4	20.5	20.0	23.7
Auxiliary Heat—Per cent	21.4	32.8	36.0	39.8	39.3	35 7	36 8	31.9	29.5	29.8	33.0
Storage Heat—Per cent	56.4	40.7	38 4	32.9	35 7	39.6	39.4	45.7	50.0	50.2	43.3

Table 4

Daily Heat Consumption of Test House During Normal Winter Weather.

	January, 1936				February, 1936						
Date	28	29	30	31	1	2	3	4	5	6	Av.
Mean Temperature Def. from 65°F.	42	45.5	48	47.5	49.5	49.5	47	44	45.5	41.5	46
Total Energy Consumption—Kwhrs.	159	143	149	154	154	154	178	179	161	39	—
Energy to Storage—Kwhrs.	77.5	75.5	78.0	78.5	79.0	79.5	107.5	106.5	107.5	0	—
Charging Time—Hrs.	10	10	10	10	10	10	10	10	10	0	—
Charging Rate—Kw.	7.75	7.55	7.80	7.85	7.9	7.95	10.75	10.75	10.75	0	—
Domestic and Unit Heater—Kwhrs	81.5	67.5	71.0	75.5	75.0	74.5	70.5	72.5	54.5	39	68.1
Effective Heat in Domestic—Kwhrs.	28	30	29	28	28	28	28	25	30	28	28.2
Heat from Unit Heaters—Kwhrs.	48.5	34.5	38.0	42.5	42.0	41.5	37.5	39.5	20.5	6.0	35.0
Heat from Storage—Kwhrs.	55.2	57.4	77.1	71.6	81.0	76.3	83.6	81.7	73.7	84.1	74.2
Total Heat Used in House—Kwhrs	131.7	121.9	144.1	142.1	151.0	145.8	149.1	146.2	124.2	118.1	137.4
Kwhrs. per Degree Deficiency	3.14	2.68	3.00	3.00	3.05	2.94	3.17	3.33	2.74	2.85	3.00
Domestic Heat—Per cent	31.4	24.6	20.1	19.8	18.6	19.2	18.8	17.1	24.1	23.7	20.6
Auxiliary Heat—Per cent	36.9	28.3	26.4	29.8	27.8	28.4	25.1	27.0	16.6	5.2	25.4
Storage Heat—Per cent	41.9	47.1	53.5	50.4	53.6	52.4	56.1	55.9	59.3	71.1	54.0

Table 5.

Daily Heat Consumption of Test House During Severe Winter Weather.

	February, 1936										
Date	7	8	9	10	13	14	15	16	17	18	Av.
Mean Temperature Def. from 65° F	57.5	64.5	59.5	52	52.5	61	63.5	64.5	61.5	50	59
Total Energy Consumption—Kwhrs	126	185	187	193	138	139	133	134	144	158	—
Energy to Storage—Kwhrs.	55.5	105.0	104.0	105.0	54.0	54.0	54.0	53.0	55.0	75.0	—
Charging Time—Hrs	5.5	10	10	10	10	10	10	10	10	10	—
Charging Rate—Kw	10.0	10.5	10.4	10.5	5.4	5.4	5.4	5.3	5.5	7.5	—
Domestic and Unit Heater—Kwhrs	70.5	80.0	83.0	88.0	84.0	85.0	79.0	81.0	89.0	83.0	82.2
Effective Heat in Domestic—Kwhrs.	28	30	28	25	28	28	28	28	28	28	27.9
Heat from Unit Heaters—Kwhrs	37.5	47.0	50.0	55.0	51.0	52.0	46.0	48.0	56.0	50.0	50.2
Heat from Storage—Kwhrs	100.5	89.4	83.3	86.6	70.7	81.1	89.3	89.2	70.5	58.8	81.9
Total Heat Used in House—Kwhrs	166.0	166.4	161.3	166.6	149.7	161.1	163.3	165.2	154.5	136.8	160.1
Kwhrs. per Degree Deficiency	2.89	2.58	2.72	3.20	2.85	2.65	2.58	2.56	2.52	2.74	2.72
Domestic Heat—Per cent	16.9	18.0	17.4	15.0	18.7	17.4	17.1	16.9	18.1	20.4	17.5
Auxiliary Heat—Per cent	22.6	28.2	31.0	33.0	34.0	32.3	28.1	29.1	36.3	36.6	31.4
Storage Heat—Per cent	60.5	53.6	51.6	53.0	47.2	50.3	54.5	54.0	45.6	43.0	51.1

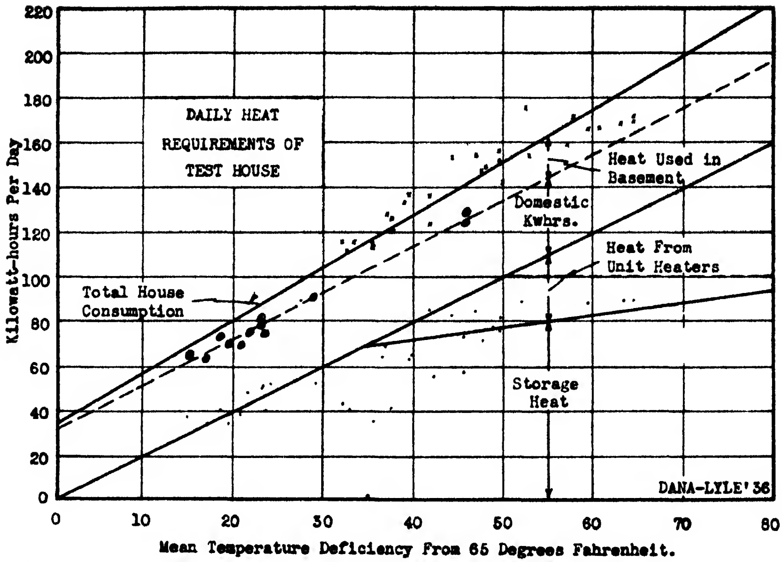

Fig. 4. Daily use of heat in the test house as affected by outside temperature.

storage unit since a large part of the basement heat eventually found its way upstairs. During the mild period in March and two days in February, only storage heat was used, with no additional heat in the basement. The dashed line on the chart indicates the heat requirements of the house without other additional heat. Domestic use of electricity is seen to account for a considerable portion of the day's heating requirements.

In most of these tests, the storage unit furnished about 50% of the total heat used in the house instead of 80% as would generally be found in practice. Domestic uses furnish approximately 20%. (See Tables 2, 3, 4, and 5.)

The lower set of test points in Figure 4 show the estimated daily use of stored heat, which is the sum of the "idle losses" from the storage and the heat removed by the fan. It was estimated that about 75% of the heat escaping to the basement was effective in warming the floors of the rooms above. A plan for utilizing a minimum size storage unit is suggested by the results shown in Figure 4. Stored heat could be used to furnish all of the heating needs of the house for days of 50 degree-days or less, with unit heaters or fuel-burning stoves used to supplement the storage in very severe weather.

PERFORMANCE OF STORAGE SYSTEM IN HOUSE HEATING

In Figure 5 is shown a composite chart of the operation of the heat storage system during the cold weather experienced from February 10 to February 20, 1936. Operation of the fan is recorded by the black dashes in the center of each chart. The storage level and temperature levels at 6 a.m., 12 n., 8 p.m., and 12 m. show the trend of conditions in the storage reservoir. The short inclined lines represent the introduction of heat during the charging period, their slopes being proportional to the charging rate employed at that time. Room temperatures and outside temperatures during the period are shown at the bottom of the charts.

The amount of heat accumulated by charging for 10 hours at the rate of 5.5 kw. was not sufficient during this period to restore the heat drained out by the fan and by idle losses during the off period of the heaters. The downward drift of the temperature continued until the minimum useful storage level was approached. The decrease of the rate of heat transfer from storage to rooms as the storage temperature decreased caused the fan to be operated longer during each period. Raising the storage temperature level by increasing the rate of charging increased the margin of useful heat and made possible a higher house-heating rate.

The performance of the heat storage system during each of the daily tests is summarized in Tables 6, 7, 8, and 9. The time required to bring the room temperatures up to 72° F., at which point the room thermostat operated to shut down the fan, depended upon the outside weather conditions at the time, the temperature rise to be accomplished, and rate at which heat was transferred from the storage to the room. The longer heating-up times shown in the tables resulted when the rate of heat transfer was but little greater than the rate of heat loss from the room at the normal room temperature. At such times, the air temperatures in the room rose to the normal somewhat slower than was usual, and the wall temperatures, which controlled the action of the thermostat, lagged considerably, thereby prolonging the initial operation of the fan.

The total daily running time of the fan was influenced by the severity of the weather, the rate of heat transfer, and the use of auxil-

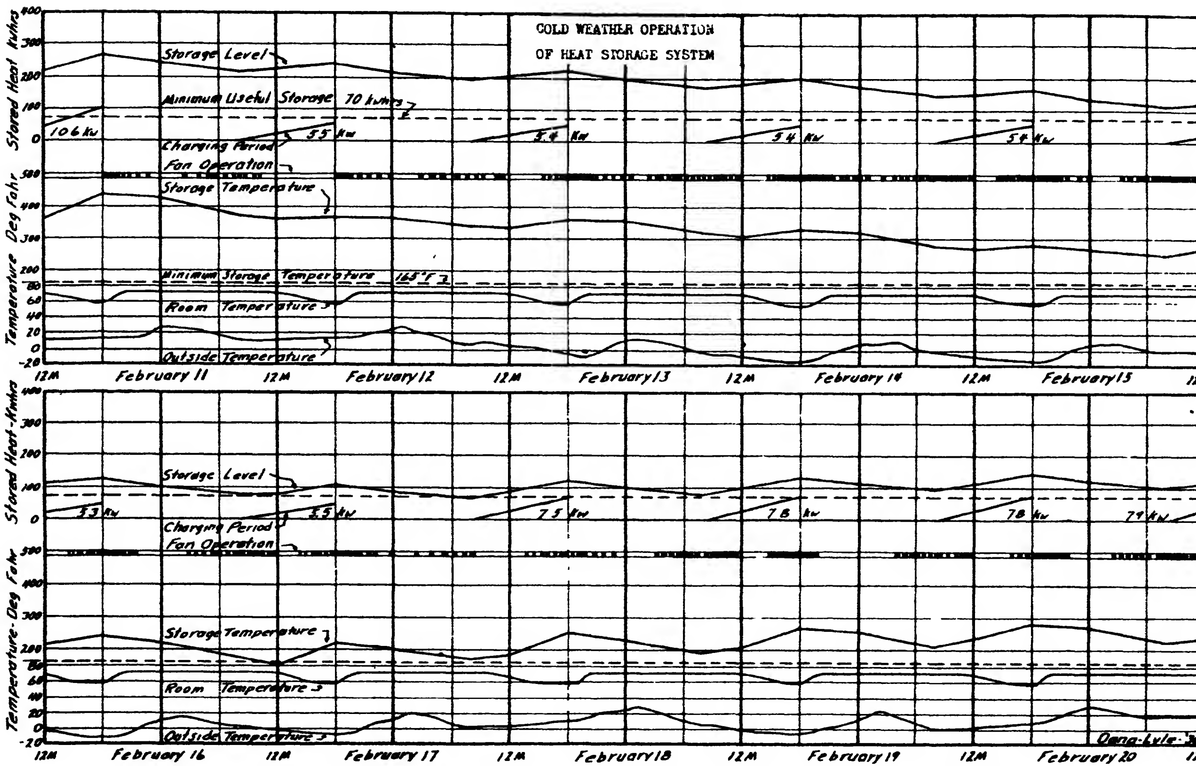

Fig. 5. Composite chart showing the operation of the storage heat system during cold weather.

Table 6

Daily Performance of Heat Storage System During Early Spring Weather.

	March, 1936										
Date	11	12	13	14	15	16	17	18	19	20	Av.
Heat Stored at 5 a.m.—Kwhrs	197.6	147.6	108.0	112.2	110.8	129.9	132.9	139.7	140.0	144.0	—
Net Increase in Storage 9 p.m.-5 a.m.—Kwhrs.	33.0	—10.6	—7.8	35.0	35.1	55.8	32.6	41.8	38.6	34.6	—
Outside Temperature—Degrees F.	35	33	36	29	26	33	37	30	33	29	—
Room Temperature—Degrees F	58	59	60	55	57	57	39	57	59	58	—
Time to 72 Degrees F.—Hrs	1.0	0.7	0.7	1.4	1.7	0.75	0.75	1.0	0.8	1.0	1.0
Fan Running Time—Hrs.	3.7	2.1	2.8	5.6	3.25	2.5	3.0	5.33	2.33	2.33	3.29
Fan Motor—Kwhrs.	1.1	0.6	0.8	1.5	0.9	0.7	0.8	1.4	0.6	0.6	0.9
Heat Removed by Fan—Kwhrs	22.3	15.8	22.0	33.1	26.9	15.6	22.8	28.2	16.9	17.3	22.1
Average Rate of Transfer—Kw.	6.03	7.53	7.86	5.91	8.29	6.25	7.60	5.30	7.25	7.44	6.95
Loss During Idle Periods—Kwhrs.	28.9	26.6	15.7	13.3	15.1	19.7	19.5	17.5	21.4	20.1	19.8
Average Rate of Loss—Kw.	1.42	1.21	.74	72	.73	.92	.93	.94	.99	.93	.95
Heat Stored at 9 p.m—Kwhrs.	164.6	158.2	115.8	77.2	75.7	74.1	100.3	97.9	101.4	109.4	—
Heat from Storage 5 a.m.-9 p.m—Kwhrs	39.4	31.8	30.8	36.7	36.7	29.6	35.0	38.3	30.6	29.7	33.9
Heating Time—Hrs	11	16	16	19	14.5	16	16	16	16	16	—

Table 7.

Daily Performance of Heat Storage System During Mild Winter Weather.

	January, 1936										
Date	18	19	20	21	22	23	24	25	26	27	Av.
Heat Stored at 6 a.m.—Kwhrs.	165 0	105.9	95.6	120 6	133 3	141.2	151.1	158.9	204.0	192.9	—
Net Increase in Storage 8 p.m.-6 p.m.—Kwhrs.	—17.3	—9.8	21.6	43 7	42.4	41.8	41.6	38.8	86.4	35.4	—
Outside Temperature—Degrees F.	25	27	28	25	29	29	27	23	20	21	—
Room Temperature—Degrees F.	56	56	57	56	57	58	58	55	55	55	—
Time to 72 Degrees F.—Hrs.	2.2	1.0	1.5	1.7	1.9	1.0	1.45	1.5	2.1	1.8	1.62
Fan Running Time—Hrs.	6.4	7.8	7.0	5.67	7.67	4.67	6.33	5.83	6.50	6.00	6.39
Fan Motor—Kwhrs.	2.3	2.9	2.6	2.4	2 9	1.7	2.1	2.2	2.35	2.15	2.36
Heat Removed by Fan—Kwhrs.	40.5	28.8	28.3	23 6	30 3	24.4	29.4	38.7	40.6	36.7	32.1
Average Rate of Transfer—Kw.	6.33	3.7	4.05	4 16	3.95	5.22	4.65	6.65	6.25	6.12	5.11
Loss During Idle Periods—Kwhrs.	23.4	13.6	7 8	13.4	13.3	18.6	15.1	16.3	23.5	24.2	16.9
Average Rate of Loss—Kw.	1.33	.84	.45	69	.81	.96	.86	.90	1.34	1.34	.96
Heat Stored at 8 p.m.—Kwhrs.	182.3	115.7	74.0	76 9	90.9	99.4	109.5	120.1	117.6	157.5	—
Heat from Storage 6 a.m.-8 p.m.—Kwhrs.	49.3	31.9	18.7	29.7	33.9	31 7	31.0	41.3	46.5	45.2	35.9
Heating Time—Hrs.	13.5	15.75	15.5	15.75	15.5	15	15	15	15	16.5	—

Table 8

Daily Performance of Heat Storage System During Normal Winter Weather.

	January, 1936				February, 1936						
Date	28	29	30	31	1	2	3	4	5	6	Av.
Heat Stored at 6 a.m.—Kwhrs.	210.4	229.5	233.9	240.1	247.8	248.9	271.8	295.4	324.7	245.4	—
Net Increase in Storage											
8 p.m.-6 a.m.—Kwhrs.	62.7	56.9	56.3	55.8	55.9	56.9	80.8	83.4	78.5	—24.7	—
Outside Temperature—Degrees F.	18	4	7	9	11	3	10	16	15	20	—
Room Temperature—Degrees F.	54	49	49	53	52	49	51	54	53	53	—
Time to 72 Degrees F.—Hrs.	1.7	1.6	1.9	1.9	2.4	2.3	2.3	3.3	2.9	2.0	2.23
Fan Running Time—Hrs.	5.33	7.0	6.2	5.1	5.2	5.4	5.1	6.4	7.1	8.8	6.16
Fan Motor—Kwhrs.	1.75	2.45	2.4	1.8	1.9	2.0	1.9	2.3	2.9	3.2	2.26
Heat Removed by Fan—Kwhrs	29.5	48.0	45.4	40.6	43.0	48.8	45.1	45.1	39.8	70.9	45.6
Average Rate of Transfer—Kw.	5.54	7.85	7.32	7.97	8.26	9.05	8.85	7.05	5.60	8.05	7.55
Loss During Idle Periods—Kwhrs.	25.6	25.2	26.6	30.0	34.7	35.4	36.5	31.9	40.1	30.6	31.7
Average Rate of Loss—Kw.	1.37	1.48	1.49	1.59	1.85	1.90	1.93	1.81	2.37	2.01	1.78
Heat Stored at 8 p.m.—Kwhrs.	147.7	172.6	177.6	184.3	191.9	192.0	191.0	212.0	246.2	270.1	—
Heat from Storage											
6 a.m.-8 p.m.—Kwhrs.	37.8	51.9	49.6	48.2	55.8	57.9	59.8	49.2	54.6	70.4	53.5
Heating Time—Hrs.	16.5	14	15.5	16	16	16	14	16	15	16	—

Table 9.

Daily Performance of Heat Storage System During Severe Winter Weather.

	February, 1936										
Date	7	8	9	10	13	14	15	16	17	18	Av.
Heat Stored at 6 a.m.—Kwhrs	202.3	213.8	232.7	250.5	223.2	199.9	165.1	129.6	106.4	125.3	—
Net Increase in Storage 8 p.m.-6 a.m.—Kwhrs.	27.3	83.3	79.7	76.5	29.4	25.8	18.9	18.2	30.0	59.3	—
Outside Temperature—Degrees F.	—9	0	—5	6	—5	—2	—13	—11	2	6	—
Room Temperature—Degrees F.	44	49	51	57	57	56	57	56	56	56	—
Time to 72 Degrees F.—Hrs	3.0	2.0	2.1	1.8	2.25	2.7	2.6	2.75	2.25	1.0	2.25
Fan Running Time—Hrs.	7.8	6.6	6.13	5.53	8.17	9.75	9.75	8.75	6.75	5.67	7.5
Fan Motor—Kwhrs.	3.4	1.6	1.8	1.45	2.50	2.70	2.7	2.8	1.3	1.5	2.18
Heat Removed by Fan—Kwhrs.	68.7	57.8	54.2	51.6	52.1	66.9	72.1	67.6	47.9	51.6	59.1
Average Rate of Transfer—Kw.	8.80	8.75	8.60	9.35	6.39	6.86	7.40	7.85	7.10	9.10	8.0
Loss During Idle Periods—Kwhrs.	27.0	25.5	29.1	34.3	25.5	19.9	17.9	15.1	10.2	15.6	22.0
Average Rate of Loss—Kw	1.67	1.46	1.64	1.86	1.61	1.40	1.26	0.99	0.59	0.85	1.33
Heat Stored at 8 p.m.—Kwhrs.	175.0	130.5	153.0	174.0	193.8	174.1	146.2	111.4	76.4	66.0	—
Heat from Storage 6 a.m.-8 p.m.—Kwhrs	71.8	60.8	58.7	56.7	49.1	53.7	53.7	53.2	40.4	45.5	54.4
Heating Time—Hrs.	16	15.5	17	24	24	24	24	24	24	24	—

iary heat. The low rate of heat transfer obtained in most of the tests was due to the difficulty of forcing a sufficient quantity of air through the storage unit and duct system with a limited temperature rise. This was possibly due to the small ducts employed, the limited air capacity of the ventilating fan, and the resistance of air flow through the rocks. The rate at which heat escaped from the storage during idle periods of the fan was proportional to the average storage level during the 24-hour period.

During the colder weather (See Table 9) the room thermostat was "set back" to 60° F, allowing the fan to operate during the night and reducing the temperature rise to be accomplished the next morning. In the spring period (See Table 6), bright sunshine contributed considerable heat each day, decreasing heat losses from the house, so that the fan was in operation at less frequent intervals. Also, the unavoidable leakage of heat from the storage unit during idle periods of the fan helped to maintain the room temperature during the warmer periods of the day.

With the exception of the fairly long periods required to bring the house to normal temperature in the mornings because of the low heating rates obtained, the rooms of the test house were maintained at a comfortable temperature. A thermostat with a differential of 2° F. was used to control the fan operation, and charts taken from a recording thermometer in the living room showed very little variation from 72° F. Heat escaping from the storage unit into the basement served to keep the floors much warmer than those of other houses without basements. Relative humidity in the rooms was controlled at about 40% by a centrifugal vaporiser.

POWER DEMAND WITH HEAT STORAGE AND UNIT HEATERS

The maximum rate of 10 kw. for charging the storage unit compares with the 12.5 kw. connected heater capacity which was used for direct heating all the other houses of the same size in Mason City. The heat loss from the test house was calculated[2] to be 9 kw. at 0° F. outside temperature, and the minimum rate for heating up from a cold condition within a reasonable length of time was approximately 11 kw.

In practical operation, the charging period for the storage unit can range from 12 to 18 hours instead of the 10-hour period arbitrarily chosen for the tests, depending upon the prevailing load conditions on the distribution system. The longer the charging period, the lower would be the charging rate necessary to accumulate a sufficient charge of heat and the lower would be the peak demand of the individual house on the system. On this basis, the maximum demand with the storage system of heating would be approximately 75% of the maximum demand where direct heating is employed, depending upon the severity of the weather, the temperature rise to be accomplished, and the acceptable time limit for attaining normal room temperature.

ENERGY CONSUMPTION WITH STORAGE AND UNIT HEATERS

During the period of the storage heating tests, the daily consumption of the other three- and four-room houses in the camp was also being noted. Table 10 presents a comparison of the daily energy consumption of the B type test house and of the average consumption of the other specially insulated B houses,[4] the standard B houses, and the C houses. Because of the basement, the consumption of the test house would be expected to be somewhat higher than the first group. Over long periods of time, the test house consumption using storage heat was about equal to that of the standard B houses. The daily consumption of the houses heated with unit heaters is seen to vary roughly with the degree-days or severity of the weather. With the storage device it was possible to carry the test house through a few cold days without increasing the daily use of energy. The fact that energy need not be drawn from the line currently with the demand for heat is a desirable feature of the storage heating method.

The effect on the individual house load curves of using power during the off-peak periods is indicated in Figure 6. A is a load curve of a representative B type house for a day of about 45 degree-days severity. A heavy peak load is thrown on the system about 6 a.m. to heat up the cold house, and energy is taken at irregular intervals and at varying rates during the day, with a peak in the early evening hours. Domestic uses and intermittent heating combine to make up the load curve shown. B is a load curve of the storage heated house for the

Table 10.
Daily Energy Use of Storage and Unit Heated Houses.

Date		Degree Days	Kilowatt-hours			
			Storage Heated B House	Average of Insulated B Houses	Average of B Houses	Average of C Housese
Jan.	16-21	34	79	75	93	118
	22-28	37	137	74	102	124
	29-30	47	146	96	115	146
	31	47½	154	102	125	164
Feb.	1	49½	154	103	126	161
	2	49½	154	102	121	161
	3	47	178	99	121	158
	4	44	179	100	116	149
	5	45½	161	98	124	151
	6	41½	39	100	118	150
	7	57½	126	141	165	215
	8	64½	185	144	166	207
	9	59½	187	133	158	206
	10	52	193	131	155	195
	11	45	186	88	110	145
	12	43	129	123	143	175
	13	52½	138	120	146	184
	14	61	139	135	157	195
	15	63½	133	126	160	209
	16	64½	134	132	162	206
	17	61	144	128	157	197
	18	50	158	122	145	186
	19	50½	166	114	146	184
	20	52	162	115	135	175
Average		46	137	103	124	156
Mar.	8-15	22	69	58	71	91
	16-23	20	66	56	69	88

same weather conditions. During the night hours a steady charging load is drawn from the line at a lower rate than the maximum used to heat the cold house of A. The load curve during the day is the usual domestic load drawn by houses with a moderate equipment of electrical appliances, and a small amount of supplementary heat from unit heaters.

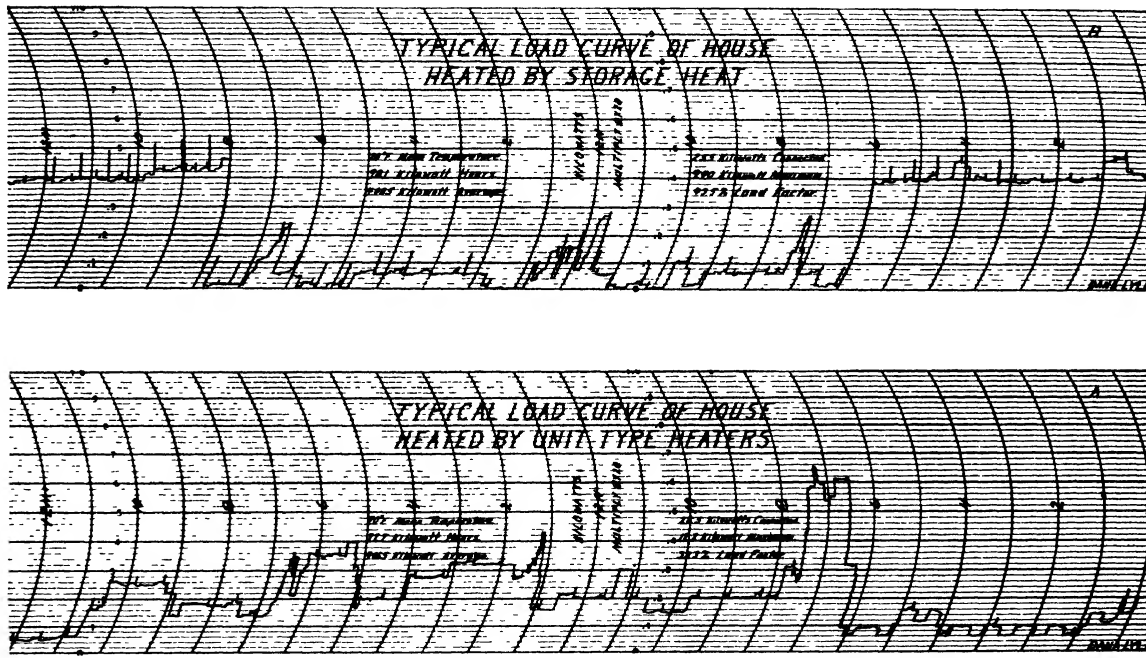

Fig. 6. Relative effect of heat storage on the daily load curves of a home heated electrically.

COMPARATIVE EFFICIENCY OF HEATING SYSTEMS

The control exercised over temperatures in the rooms affects the efficiency of any heating system to a considerable extent. If rooms are heated above the temperature necessary for comfort, the losses are increased, and the occupants frequently open windows or doors to regulate the temperature The total heat consumption during the day is consequently higher than if the temperatures had been held at a reasonably steady value Automatic control of temperature is gaining in favor because it adds to the comfort, convenience, and efficiency to be obtained from a heating system.

The efficiency of fuel burning domestic heating systems is considered to be the overall efficiency of the fuel combustion equipment, and commonly ranges between 25 and 60%. The efficiency of direct electrical heating, on the other hand, is 100% since the electrical energy is changed into heat by a perfect conversion process within the space to be heated However, the heat generated may be lost or wasted in many ways, so that the overall effectiveness of application of the heat to the room is an uncertain quantity depending upon loss through open doors and windows, the control of temperatures in the room, and the varying habits of occupants

Only useful heat should be considered in estimating the efficiency of a heating system, i e heat which is useful in maintaining comfortable temperatures in the living areas during periods when they are occupied. This includes not only the heat which warms the air in the rooms, but that which warms the floor, walls, partitions, ceilings, and furnishings of the rooms, thus reducing the transfer of heat from the air to the surrounding surfaces. When the house is unoccupied for periods of several hours duration, heat used to maintain the normal temperature is not useful in promoting human comfort and is consequently of little utility, except for maintaining wall and floor temperatures and in preventing freezing temperatures in the house in very cold weather Much waste of this sort is unavoidable.

In fuel burning systems, a fire is usually kept burning for about 16 hours during the day and allowed to go out at night except in very cold weather During the heating period of the day, heat is radiated from the furnace in the basement at varying rates, but most of this heat rises through the basement ceiling and warms the floors

of the rooms above. During the night, usually, the radiation loss is greatly reduced since fires are banked or allowed to go out.

The desirability and importance of good control over the leakage of heat from the storage unit is apparent, especially in mild weather with the accompanying infrequent and short periods of heat demand. In cold weather, when heat is required throughout the occupied periods each day, however, heat escaping from the storage unit is not objectionable, since for the most part, it takes the place of an equivalent amount of heat supplied through the ducts.

The conversion of electrical energy to heat in a heat storage device is 100% at the time heat is being released in the storage compartment. While being held there in readiness to heat the house, however, an unavoidable leakage is continually taking place, the rate depending upon the design of the storage unit, the internal temperature, and the amount of insulation built around the compartment. This loss is similar to the heat radiated from a furnace, except that furnace losses are present only when fuel is being burned, while leakage from the storage unit takes place continuously. With storage units located in the basement, most of the heat radiated to the basement finds its way through the floors to the rooms above. Some of this heat, in either case, is lost by transmission through the walls and floor of the basement, and therefore serves no useful purpose. Also, during the hours of retirement at night, the continual loss of heat from a storage unit represents an actual loss, since it does not necessarily further the comfort of the occupants. In very cold weather this loss becomes of some use in avoiding freezing temperatures in the house and in decreasing the temperature rise to be accomplished the next morning.

The overall efficiency of the experimental heat storage system during normal winter weather was estimated, following the above considerations, to be 95 to 98% as compared to the 100% efficiency for space heating with unit heaters.

REQUIREMENTS OF SATISFACTORY ROCK STORAGE SYSTEMS

A storage heating system of the type described in this bulletin should be capable of furnishing the full heating demands of the house in which it is installed, with a degree of comfort and convenience equal

to that of other automatic heating systems during the coldest weather of the heating season. The heat should be delivered to the rooms at a maximum rate sufficient to raise the temperature from a night level of about 60° F. to normal in a short time in the most severe weather. The heating-up time will vary with individual preference from one-half to one hour.

It should be possible, by means of simple adjustments, to decrease the rate of heat delivery to meet the needs of the milder periods of the heating season. Room temperature can be more evenly controlled by a thermostat when the rate of heat input is but little greater than the rate at which heat escapes from the house. The temperature of the air issuing from the registers should be controlled within the range of 120° to 180° F. to obtain the necessary heating rates without causing discomfort due to the contrast between the current of hot air and the relatively cooler slow-moving air in the rooms.

A storage system using hot air as the heat transmitting medium is adaptable to the inclusion of standard air conditioning features such as air washing and humidification, etc. The inherent advantages enjoyed by users of electrical heat with unit heaters are obtained also with this electrical storage system, which includes some of the added advantages of the hot air system.

Sufficient heat must be held in a practical storage unit at a reasonable temperature to supply the house for one day of the most severe weather expected at the location. Normal room temperature is usually maintained for about 17 hours with a lower temperature being maintained at night. Storage of more than one day's supply is unnecessary since it involves greater losses at the higher temperatures or requires a larger volume of storage material. The service rendered by the present day utilities is sufficiently reliable to preclude the possibility of extended service interruptions. The amount of heat which will be used in a day of severe weather will depend upon the size and construction of the house, the amount of insulation used, the means employed to control infiltration, the wind velocity and exposure, and the difference of temperature between the rooms and the outside. The loss of heat from a house under various weather conditions can be estimated by well known methods.[8]

[8] See American Society of Heating and Ventilating Engineers Guide.

During extremely cold weather, it may be desirable to use auxiliary heat from small unit heaters or small gas or coal stoves to supplement the storage system, particularly during the morning pick-up period. A properly designed heat storage system, however, should be capable of distributing ample heat throughout the house to maintain comfortable temperatures without assistance. The use of auxiliary heat should be avoided as much as possible for greater convenience in operation and because of the possible higher rate per kwhr. charged for demand heat.

SIZE AND CONSTRUCTION OF HEAT STORAGE UNITS

The size of rocks to be chosen for the storage material of a rock heat storage unit should be neither too large nor too small. If too large, the possible rate of extraction of the stored heat with prolonged operation will be slow, while if they are too small, the air passages through the pile will be restricted, which again will retard the extraction of heat by resisting the flow of air Sizes between 3 and 6 inches in diameter seem to be most suitable. The rocks should be carefully packed to give as high storage capacity in the enclosed volume as possible, but at the same time, care should be exercised to provide sufficient void space for the necessary volume of air to flow through without undue resistance. Rocks of the size used in the experimental storage unit (3 to 6 inches in diameter) can be piled, including the necessary space for distributing ducts and heater elements, with a space factor of about 85%. That is, the mass of solid material will occupy 85% of the enclosed space with 15% being occupied by air. The volume necessary to enclose the amount of storage materials required to store the necessary quantity of heat can thus be roughly estimated.

The upper limit to the storage temperature is determined by the ease of control of the mixing of the stream of hot air through the storage unit with the cold air by-passed around the unit, as well as by the proportionately higher losses that occur at very high temperatures. Figure 7 shows the volume mixing relations required to control the temperature of the air sent to the rooms at different temperatures. More uniform control will be obtained when mixing about equal volumes of hot and cold air, than when a large quantity of cold air is

required to temper a small quantity of very hot air. A maximum temperature of about 500° F. will allow satisfactory regulation of the duct temperatures with simple automatic damper control arrangements.

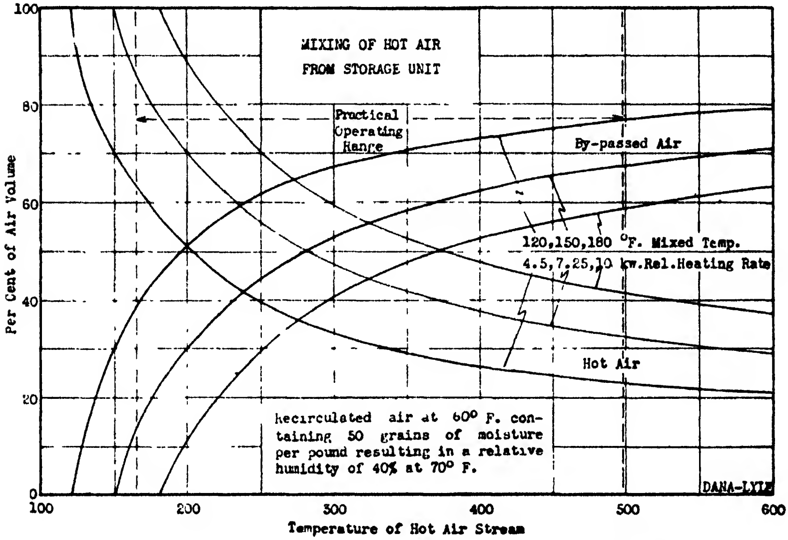

Fig 7 Showing the practical range of temperatures which may be employed in the air mixing chamber in order to assure correct air temperatures at the registers

The necessary charge of useful heat for a day's heating must be stored in the material above a temperature of about 165° F. At this temperature, air flowing through the storage material will emerge at about 120° F., which is about 20° below the usual temperatures of air at the registers of hot air heating systems. A minimum charge of heat, depending upon the volume and specific heat of the storage material used, must first be accumulated in the unit, the quantity of useful heat to care for the day's heating needs being stored above this level.

The length of the off-peak period, which will vary with the system loading from possibly 10 to 18 hours per day, will have a bearing on the size of the storage unit and on the use of auxiliary heat. The minimum charging time of 10 hours can occupy one continuous period during the night, while longer charging times will make necessary one or two shorter periods during the day, which will usually be staggered

at the will of the utility to avoid the system peaks. During the daytime periods, a portion of the heat generated by the heating elements can be made immediately useful as demand heat in heating the house. The required storage capacity of the storage unit can therefore be lower by the proportion of the day's heating requirements drawn during these periods.

The amount of useful heat stored at the maximum temperature will be in proportion to the volume of the storage material, and the loss of heat by radiation from the sides of the enclosure will be in proportion to the exposed area. The shape of the enclosure should approximate a cube since the surface from which radiation losses can occur will then be a practical minimum The volume of storage material used may be the minimum quantity that will store a supply of heat for the needs of the coldest day between the limits of 165° and 500° F.

Because of the relatively high storage temperatures, a large "heat head" is set up which will cause considerable loss of heat by convection if there are openings or small cracks in the upper portion of the enclosure. Therefore, the cold and hot air ducts should be led into the storage unit from the bottom to form a natural heat trap. This arrangement will make for better control of high temperature air during operation as well as reduce the loss of heat during idle periods.

The movement of air through the storage material causes a drift of heat from the cold air entrance to the hot air exit. The higher temperatures at the exit end of the test storage unit caused a greater heat loss by radiation than in the other regions. For this reason, it is suggested that the hot air be removed from the storage unit at the center of the bottom of the pile and the cold air introduced around the sides of the bottom. The hottest portion would then be kept in the center of the pile, and the sides would be cooler, thus reducing the loss of heat by radiation from the storage unit. (See Figure 8).

The amount of insulation to be placed around the storage unit will be determined by the economic balance between the investment in insulating material and the value of the heat saved which would otherwise be wasted during periods when heat is not required in the house.[8] Because of the higher temperatures at the top of the storage space, more insulation should be provided on the top than on the

sides. In addition, it will be desirable to place ample insulation on the hot air pipes to minimize loss of heat to unused spaces. The importance of sufficient insulation around the storage unit should be as evident as is the importance of the insulation of the house itself in conserving heat. The higher price of electricity compared to that of common fuels tends to emphasize the necessity for efficient use of the heat.

The design of the air passages in the storage unit and of the hot and cold air ducts should conform with good heating and ventilating practice. The velocity of air in the storage unit and ducts should be limited to about 500 feet per minute and to 300 f.p.m. at the hot air registers to minimize noise due to the air flow. The necessary cross-section of air ducts and passages will be determined by the volume of air required to transfer heat at the maximum desired rate with the permissible temperature rise. The ventilating fan should be of sufficient capacity to force an ample quantity of air through the storage unit to attain the necessary maximum rate of heat transfer, without exceeding the temperature range of 120° to 180° F

The tempering of the very hot air from the storage unit with cold by-passed air should be controlled to give mixed temperatures of 120° to 180° F. depending upon the severity of the weather and the heating rate desired. When a minimum amount of the storage material is used, the temperature level in the storage unit will vary throughout most of the usable range during severe days, so that automatic control of the mixing is very necessary (See Figure 7). A simple vane damper at the junction of the hot air pipe from the storage unit and the by-pass pipe, controlled by a bimetallic element in the hot air stream, will be sufficient to properly control the mixed air temperature. Since the resistance of air flow through the storage unit is much greater than through the by-pass, a damper should be provided in the by-pass pipe to aid in controlling the flow of air through the storage unit Another damper, in the cold air return pipe, controlled from the living quarters, should be provided to regulate the quantity of air passing through the system and provide rough regulation of the heating rate.

The heating elements should be of high quality, ruggedly built and well supported, and provision should be made for withdrawing

them for inspection and repair. They should be capable of withstanding temperatures of about 1000° F. which will exist in their vicinity during charging, and should be divided into sections which, with suitable controls, will furnish, say, 25%, 50%, 75%, and 100% of the maximum connected capacity. This range of charging rates, under control of the householder, will enable full advantage to be taken of the off-peak periods of the system with the minimum demand consistent with the daily heat requirements. A simple control panel should be provided for contactors, heater control switches, and time switches, necessary for the proper control of the heating equipment. The thermostat used for controlling the storage temperature should be calibrated so that it could be set at will at predetermined temperatures for seasonal control of the storage heat level.

SUGGESTED DESIGN OF PRACTICAL STORAGE UNIT

A typical heat storage unit for use in a home of size and construction similar to the test house in Mason City is shown in Figure 8. The base of the unit may be formed of pre-cast insulating concrete with intake and outlet air ducts incorporated. If the unit is placed on the first floor level, rather than in the basement, the insulated side walls can be finished to serve as part of the walls of the rooms surrounding it. In such a plan, all of the heat escaping from the storage unit will be delivered into the adjacent rooms.

According to Figure 4, the daily consumption of the test house in weather of 65 degrees deficiency was 135 kwhrs. Allowing a margin of 15 kwhrs. for unusual demands, the unit should have a storage capacity of 150 kwhrs, of useful heat.

From the tests it was found that .0065 kwhrs. of heat could be stored in each cubic foot of the storage unit per degree F. temperature rise. Therefore, the storage volume required to store 150 kwhrs. of heat between the limits of 165° to 500° F. would be:

$$\text{Volume} = \frac{150 \text{ kwhrs.}}{.0065}$$

$$= 68.5 \text{ cu. ft.}$$

The overall size of the heat storage material is about 68.5 or 70 cu. ft. or a cube of about 4.1 feet on each side. A double brick wall

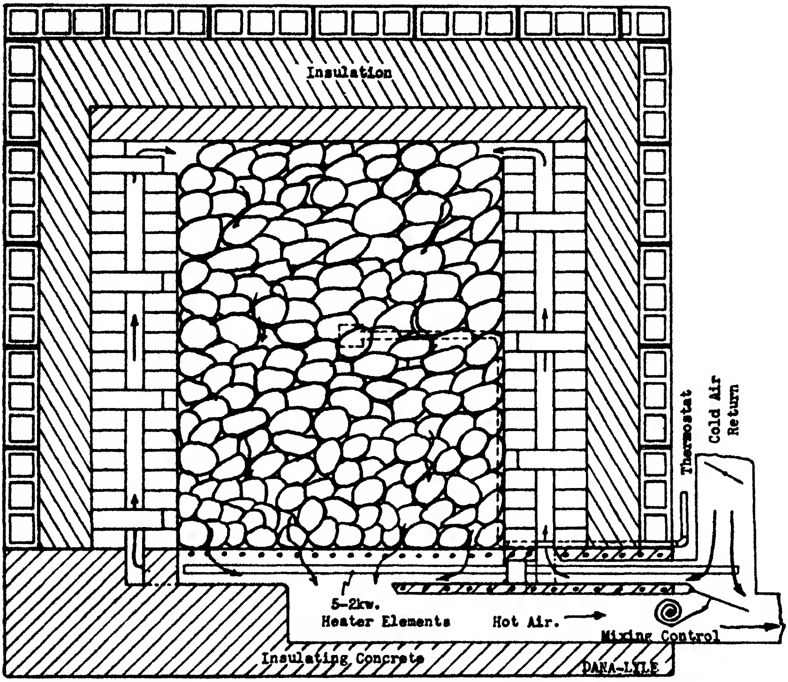

Fig. 8 Suggested design of a heat storage unit for practical off-peak storage heating of a small home using rock and brick as the storage medium.

with an air space between is provided to enclose the rocks. The cold air from the return pipe flows through this air space, making use of the counterflow principle to reduce the temperature at the outside of the storage space, which will aid in reducing the idle losses. The heated air is removed from the center of the foundation block, thereby maintaining the region of highest temperature in the center of the storage space.

The brick retaining wall may be of common brick laid with a thin mortar of fire clay to minimize possible cracks permitting leakage of hot air under high temperature heads. A homogeneous cap of insulating concrete over the pile of rocks forms a firm support for the top layer of insulation as well as reducing leakage of air and providing additional insulation. Six inches of a loose fill type insulating material such as Unifill or Zonolite which is fire proof and vermin proof was calculated to be an economical thickness for the insulating layer. This

amount of insulation allows a loss of about .8 kw. at 500° F. (See Fig. 9). Outside walls of 4 inch hollow tile for retaining the loose insulation layer also serve as additional insulation, making the outside dimensions about 6'-6" each way. With this construction, the losses from storage by conduction and leakage of hot air will be controlled to a low value.

The heating elements are arranged to be slipped into slots in the pre-cast base block with a grid of iron bars above them to support the rocks and allow free circulation of air. Five 2 kw. elements are provided, each controlled by a hand-operated switch. One element is arranged to be controlled along with the fan by the room thermostat to provide demand heat in mild spring and fall weather when but little heat is needed or during the "on-peak" hours of very severe winter weather to assist the storage The heaters being located at the outlet end of the system would make possible the delivery of the heat directly to the rooms when the fan was in operation.

SEASONAL OPERATION OF HEAT STORAGE SYSTEMS

In operating this storage heating system through the heating season, a schedule of operation such as shown in Figure 9 could be followed. For the occasional cool days of late summer, the demand unit could be utilized under control of the room thermostat. It would thereby not be necessary to maintain a store of heat through possible periods of warm weather of several days' duration in order to have heat available for the cool days When the days begin to be uniformly cool, one of the 2 kw. heater units could be connected for off-peak operation, the storage thermostat being set to cut off the electricity when the internal temperature reached 250° F. The dampers could be adjusted to obtain a low rate of heat flow to the rooms as desired for uniform temperature regulation The room thermostat, by controlling the operation of the fan, would then maintain the required room temperature.

As the season advanced, the days becoming colder, additional 2 kw. units could be connected for off-peak operation, the storage thermostat cut-off point could be advanced, and the heating rate increased by adjusting the dampers to permit the flow of more air through the system. During the severe weather of midwinter, a maxi-

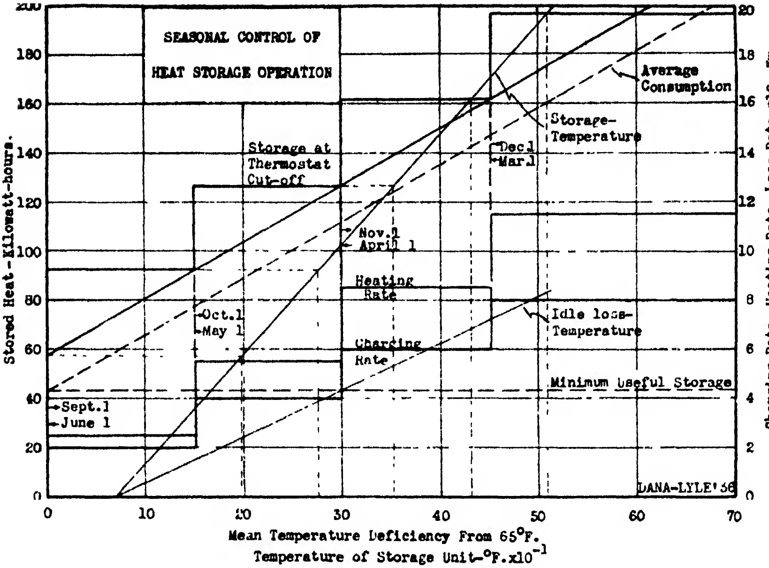

Fig 9 Suggested program of seasonal operation of a practical storage heating system.

mum of 8 kw could be connected for charging the storage unit, the storage thermostat could be set at 500° F and the dampers adjusted for the maximum rate of heat delivery During this period, it would be possible, if necessary, to operate the 2 kw demand unit during extremely cold periods under control of the room thermostat to assist the storage. As the weather became less severe in the spring, the procedure would be reversed, disconnecting heater units, lowering the storage thermostat cut-off temperature, and reducing the flow of air through the system For the occasional cool days of late spring, the demand unit could again be connected under control of the room thermostat when heat was desired, allowing the storage material to cool

By following the program of operation described above, the householder would be assured of a plentiful supply of heat to carry his household through one day of the currently expected weather. This would avoid maintaining a relatively large quantity of unused heat in storage from day to day, with the proportionately higher rate of heat loss at the higher storage levels. Better control of the room temperatures would be obtained, and the seasonal efficiency of the heating

system would be maintained at a high value. This sequence of operations, while requiring several adjustments to be made to the heating equipment, could be readily accomplished by the average householder by following specified directions. Such a heating system would afford all of the advantages of full automatic operation and provide comfortable and healthful domestic heating, with the possibility of incorporating winter and summer air conditioning features.

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MONTHLY BULLETIN
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Vol. XX July, 1937 No. 2

Physical Properties of Magnesium Alloys

No. 1—Precipitation Hardening of A Magnesium Alloy Containing 8% Aluminum

by James G. McGivern
Assistant Professor of Mechanical Engineering

and Clinton A. Wilkinson
Longview Fibre Company

ENGINEERING BULLETIN No. 50
ENGINEERING EXPERIMENT STATION
H. V. Carpenter, Director

PUBLISHED BY THE STATE COLLEGE OF WASHINGTON

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TABLE OF CONTENTS

Precipitation Hardening of A Magnesium Alloy Containing Eight Per Cent Aluminum

James G. McGivern and Clinton A. Wilkinson

I. Introduction

In the past few years considerable attention has been centered on magnesium and magnesium alloys as materials of engineering, but the possibilities of varying and controlling their physical properties by various heat treatments has not received the attention it deserves. The purpose of this paper is to give the results of an investigation on the heat treating characteristics of an extruded alloy containing 91.8% magnesium, 8% aluminum and 0.2% manganese. For this work hardness was used as the index of change in physical properties and the technique of hardness testing is described. Inasmuch as the observed structural changes accompanying the change in hardness do not indicate that the mechanism of precipitation hardening is similar to that reported for other metals a discussion of this phenomenon is included.

II. Testing Procedure

The experiments were carried out on five-eighths inch diameter extruded rods furnished by the Dow Chemical Company. The hardness readings were taken on the Rockwell Hardness Tester which records the difference between a constant value and the depth of impression of a steel ball under a definite load. This constant minus the depth of impression is called the Rockwell number and is read directly on the dial. To insure a sufficient range in hardness values a 1/8" ball and a one hundred kilogram load were used and the readings called Rockwell E readings were read on the C scale. Five readings were taken along the periphery and the hardness readings reported are those taken on the curved surface of the rods and by use of Fig. 1 these numbers may be converted to corresponding values taken on a flat surface. Duplicate runs were made for all curves given.

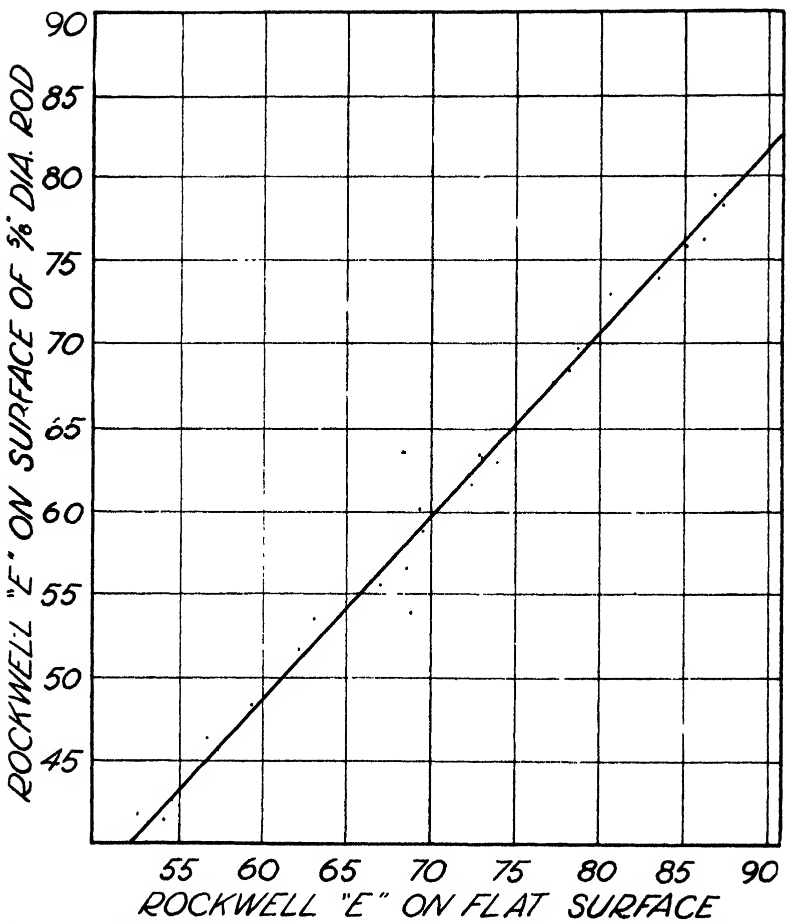


Fig. 1. Relation between curved surface and flat surface hardness readings for five-eighths inch diameter rod.

III. Principles of Precipitation Hardening

Magnesium can retain under equilibrium conditions 11% of aluminum in solution at its eutectic temperature and only a fraction of this amount at room temperature. The rate at which this excess aluminum will precipitate from the magnesium on cooling is much slower than ordinary quenching rates and at room temperature the magnesium will be super-saturated with aluminum. At this temperature the metastable

condition will be maintained and the physical properties of the material will not change with time. The solid at this temperature is too viscous and prevents the excess aluminum from separating out of the magnesium. By heating to certain low temperatures, however, the viscosity will change without appreciably altering the solubility relationships and the aluminum as part of an inter-metallic compound Mg_3Al_2[1] will form and cause a change in the physical properties of the metal. This process may be termed aging[2] and the change in hardness accompanying the phenomenon is called "precipitation hardening."

The heat treatment necessary for controlling this process consists of three distinct steps: (1) Heating the alloy to a temperature sufficient to cause all the aluminum to be in solid solution with the magnesium and to relieve the material of any strain hardening that may be present (2) To quench it from this temperature at a rate faster than the precipitation rate, thereby producing a super-saturated solid solution capable of aging (3) To heat to certain temperatures to allow for the precipitation of particles of Mg_3Al_2 from the super-saturated solid solution.

From a result of their work on duralumin, Merica, Waltenburg, and Scott,[3] explained the hardness change with aging by assuming the precipitation of submicroscopic particles of a hard inter-metallic compound To justify how this so markedly changed the hardness, Jefferies and Archer[4] stated that these particles on the potential planes of slip act as keys and mechanically prevent slip. To explain the change in electrical resistance and the apparent lack of change in lattice parameter with the aging of duralumin, Merica[5] revised his earlier theory. In its new form the theory attributes the increased hardness to the atomic forces set up in the formation of the intermetallic compound and indicates that when the particles are actually formed and precipitated, a softening takes place which is termed overaging. The previous explanation of overaging was that the size of the particles formed became greater than that necessary to produce maximum hardness.

[1] Jefferces, Z., and Archer, R. S., "Science of Metals," p 234, McGraw-Hill Book Company, New York, 1924.
[2] Harrington, R. H., "Age-Hardening Alloys and Their Application," *General Electrical Review*, March, 1936, *Vol.* 39, No. 3, p 124
[3] Merica, P. D., Waltenberg, R. G., and Scott, H., "Heat Treatment of Duralumin" Bull. Am. Inst. of Mining Engrg., p. 913, June, 1919.
[4] Jefferies. Z., and Arched, R. S., Chem. & Met. Engrg. (1922), 26,449.
[5] Merica, P. C., Trans. of A.I.M.E., (1932)

Another explanation for the increased hardness occurring without corresponding micro-structural changes is given by Guerther[6]. He assumes an intermediate colloidal state existing between the time of the initial state, expressed by the original undistorted space lattice, and the final state represented by a complete formation of the precipitated particles. This intermediate state is one involving best mechanical properties and is termed colloidal because of the assumption that initial precepitation occurs in atomic or nearly atomic dispersion which in many respects is analogous to a colloidal solution.

In the evidence reported in this paper it will be seen that the mechanism of precipitation for this magnesium aluminum alloy is not characteristic of that for duralumin and the microstructure reveals the phenomenon that does take place quite clearly.

IV. Solubility of Aluminum in Magnesium

The magnesium aluminum relationships are complicated and the system contains two compounds and three eutectics. The metals are mutually soluble in each other to a limited amount in the solid state and their compounds also form solid solutions. The change in solubility of aluminum in magnesium with temperature has been studied by many investigators but as yet the exact nature of the relationship has not been agreed upon. Hanson and Gaylor[7] give the solubility of aluminum in magnesium as 2.6% at 150°C. and Archer[8] by hardness tests concluded that the limit of solid solubility at room temperature is between 5% and 6%. Meissner[9] gives a probable value of 7% and Gann and Winston[10] of 6% while Schmidt and Spetaler[11] in the diagram of Fig. 2 give a value of 7%.

All the above results are in agreement that the solubility at room temperature is less than the 8% alloy being considered so that aging is possible but the exact amount of super-saturation obtained at room temperature by quenching has not been established. Fig. 2 shows the magnesium rich portion of the diagram describing the relationship

[6] Guerther, W., "Colloidal Conditions in Metal Crystals," Colloid Chemistry edited by Alexander, J., Vol. III, p. 441, Chemical Catalog Company, New York, 1931.
[7] Hanson, G., and Gaylor, M. L. V., "Constiution of Alloys of Aluminum and Magnesium," Jr. Inst. of Metals, 1920, Vol. 24, p. 201.
[8] Archer, R. S., "Hardening of Metals by Dispersed Constituents Precipitated from Solid Solutions," Trans. A.S.S.T., 1926, Vol. 10, p. 718.
[9] Heissner, K. L., "Age Hardening Tests with Elektron Alloys," Jr. Inst. of Metals, 1927, Vol. 38, p. 195.
[10] Gann, J. A., and Winston, A. W., "Magnesium and Its Alloys," Ind. Chem., 1927, Vol. 19, p. 1193.
[11] Schmidt and Spetaler, Jr. Inst. of Metals, Vol. 38, p. 195.

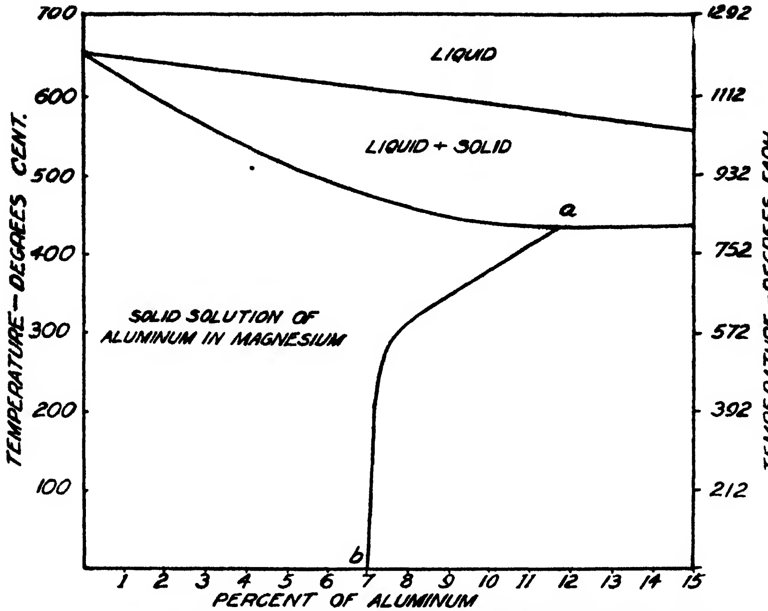


Fig. 2. Magnesium rich portion of magnesium aluminum series.

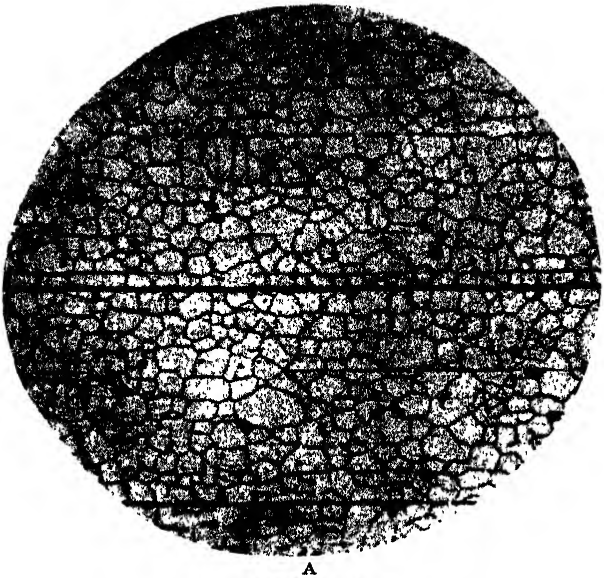
between the two metals. In this figure the line ab illustrates how the solubility of Al in Mg varies from 12% at the eutectic temperature (817° F.) to 7% at room temperature. If the diagram is correct there is practically no change in solubility when heating from room temperature up to 425° F. and but little more up to 575° F.

V. Solution Treatment

The solution treatment will cause any precipitated particles to go back into solution and also relieve the material of the effects of any strain hardening it may possess. In this problem we have an example of each of these functions of the annealing process working separately and another of them working together.

The extruded material in the "as received" condition has an extrusion temperature[11] represented above the saturation line given in Fig. 2. The material in this condition is a super-saturated solid solution of Al in Mg as revealed by its micro-structure and by the fact

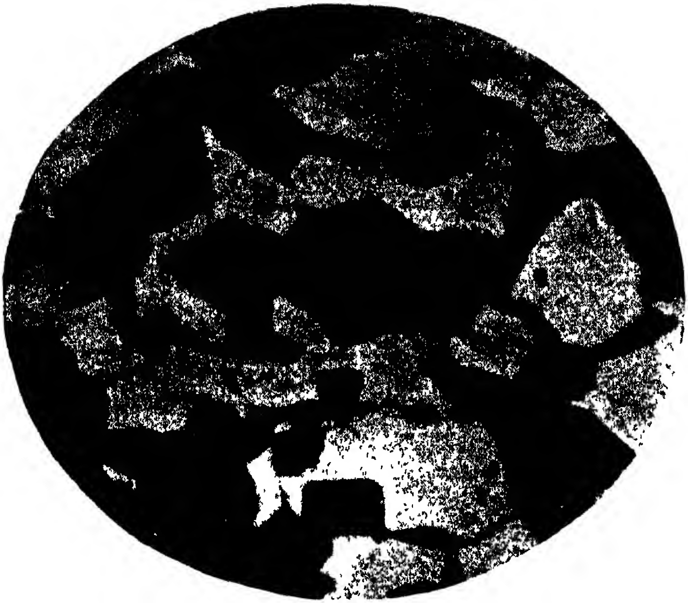
[11] Gann, J. A., "Magnesium-Industries Lightest Structural Metal," Paper presented at Western Metal Congress, San Francisco; February 17, 1931.



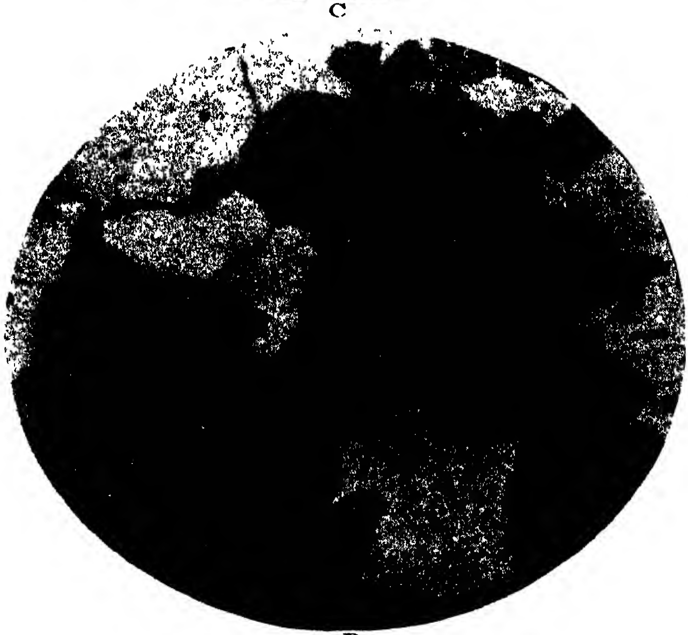
A

B

Fig. 8. Microstructures of magnesium alloy (8% Al). Specimens A and B are in as received" condition. Specimen C has been strain annealed and fully aged at 300° F. Specimen D has been solution annealed three minutes at 775° F. from condition of Specimen C.



C



D

that it will age from this condition. Fig. 3A and 3B show microstructures taken from longitudinal sections in the initial condition. Fig. 3A was taken at 100 diameters magnification while Fig. 3B was taken at 800 diameters magnification. These pictures show up the inclusion stringer, a fairly uniform grain structure, a slight twinning effect and a small amount of visible percipitation along the grain boundaries and along the inclusion stringer. The relatively low hardness of 65 Rockwell E which the material has may be attributed to the strain hardening associated with the extrusion process plus a slight effect of precipitation.

The annealing process for the material in this condition is essentially one of strain hardening relief. The change of hardness immediately following quenching after having held the material for different time intervals at two different temperatures is given in Fig 4A. The oxidation that normally would take place when annealing at 800°F. was prevented by covering the specimens with iron filings. The 775°F.

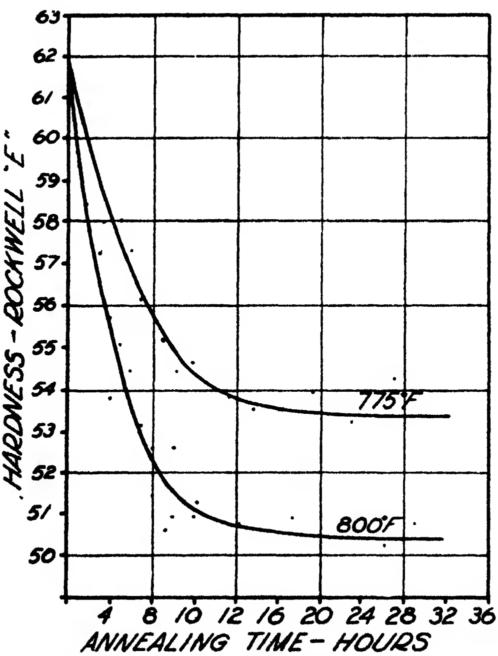


Fig. 4A. Solution treatment from the as received" condition.

annealing treatment from sixteen to twenty hours was the one used to anneal the worked material prior to any precipitation treatment, but in some cases other annealing treatments were used in order to show the effect of initial hardness on the final aging condition or the rate of hardness change with time. The final hardness was not effected by the quenching rate and the hardness obtained after allowing specimens five hours to cool from the annealing temperature was within a point of that obtained by a brine quench at 7°F. Other quenching baths with temperatures varying from 70 to 180 degrees F. showed no difference.

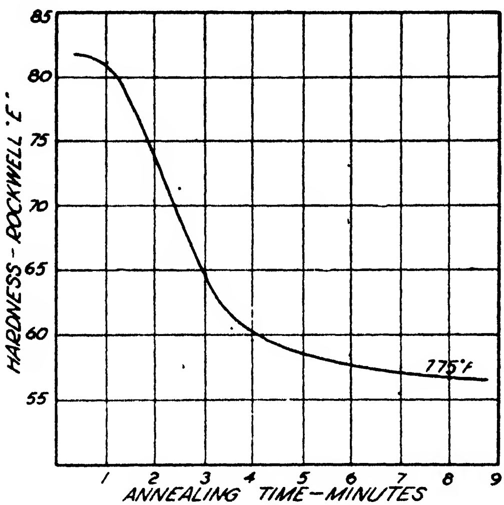


Fig. 4B. Solution treatment from the aged condition.

The solution annealing characteristics of a specimen that had first been strain annealed by a sixteen-hour treatment at 775°F. and then aged at 300°F. to allow precipitation hardening to take place is different from the strain annealing applied to the extruded metal. In this second case the solution anneal has as its function the dissolving of the precipitated particles back into solid solution. The curve representing the change of hardness with time for this condition is given in Fig. 4B. This solution anneal is completed in ten minutes while the strain anneal which has only half the hardness range requires eighteen hours. This shows quite strikingly the difference between the two

cases. The micro-structures of Fig. 3C and 3D show the changes taking place in the solution anneal around and in precipitated areas. Fig. 3C shows the material at the end of aging which is the beginning of the solution anneal and 3D gives the structure after it has been annealed at 775°F. for two minutes and then quenched. The dissolving of the precipitated area is clearly shown. The initial boundaries of the precipitated area are seen to be maintained and the dissolving of the inter-metallic compound is within this area These pictures were taken at 400 diameters magnification.

VI. Aging from the Annealed State

After annealing to relieve the material of the effects of any strain hardening or precipitation, the specimens were quenched and aged at various temperatures to allow precipitation to take place. The amount of super-saturation produced by quenching from 775°F. is uncertain and on the basis of the data given, under the solubility relationships, may vary from a maximum of 6% on a basis of 2% solubility at room temperature to 1% on the basis of 7% solubility at room temperature.

Quenching from the annealing temperature will give a super-saturated solid solution and the amount and rate of precipitation of Mg_4Al_3 from this solution will vary with the aging temperature. As the temperature increases the viscosity of the metal will decrease, thereby aiding the process. Increased temperature may also mean a decrease in solid solubility which would decrease the amount of super-saturation and hence the tendency to age Fig. 2 does not indicate much change in solubility below 575°F. but a different form of curve "ab" as reported by other investigators, previously listed, indicates a change below this temperature.

Fig. 5 illustrates the effect of different aging temperatures when aging from the same initial hardness produced by a sixteen hour 775° F. anneal. There is practically no aging at room temperature and at 260°F. the rate as measured by change of hardness with time is slow but does reach the same hardness as the 300°F. treatment although this is not shown on the diagram. The temperature range between 260°F. and 360°F. is rather critical and the maximum hardness is obtained by 300°F. aging. Above this temperature the change in solu-

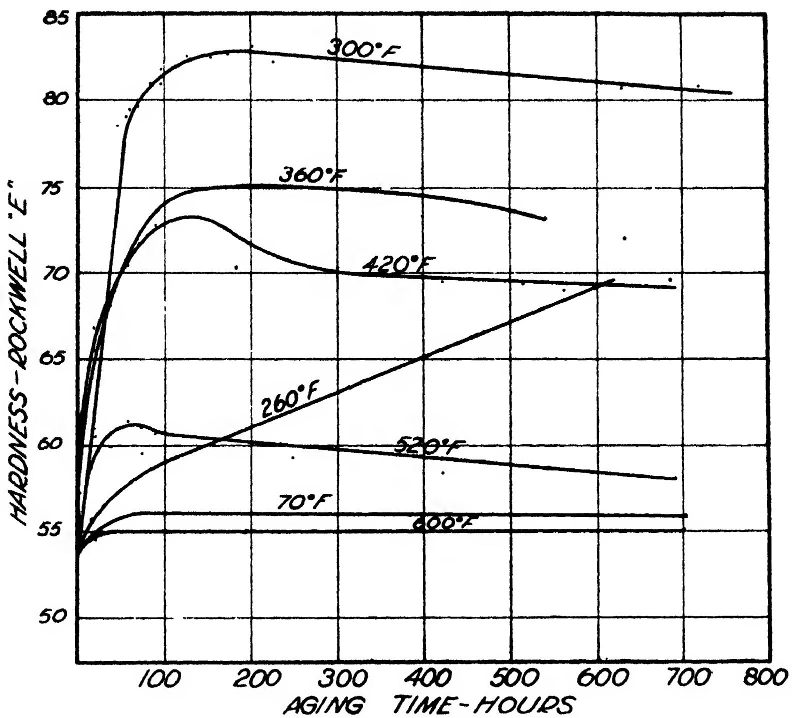


Fig. 5. Effect of temperature on aging from the annealed state.

bility seems to have an effect and the drawing shows lower final hardnesses with the higher temperatures and practically no change with a 600° F. treatment

It should be noticed that the usual incubation period reported for most aging systems is absent in this alloy. An incubation period is characterized by being a time interval at the beginning of aging where no hardness change is observed. These curves also indicate that overaging is seen to occur to some degree for all aging temperatures but to a marked degree for the 420°F. and 520°F. aging.

The curves of Fig. 5 would have been modified if the aging had begun from a different initial condition. To illustrate that the rate of aging and the final hardness attained is a function of the initial hardness, 360°F. aging tests were made from materials having different hardnesses. The initial hardness values were obtained by a 775°F

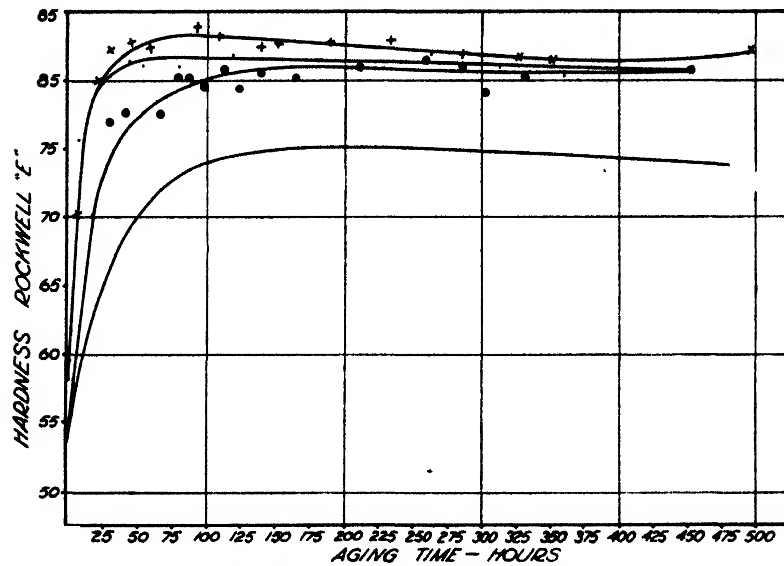


Fig. 6. Effect of initial hardness on 360° F. aging following partial anneal.

solution treatment and regulating the time of anneal according to Fig. 4A to give the desired hardness. Fig. 6 gives the results of these tests and brings out the fact that the greater the initial hardness the shorter and time necessary to attain maximum hardness and there is an optimum initial condition for this aging temperature that will give a hardness equal to that obtained by the 300°F. aging given in Fig. 5. The increased rate of aging accompanying the increased initial hardness may be accounted for by the fact that the material was not completely relieved of its strain hardening by the incomplete annealing treatment.[13] This distorted space lattice has less power to retain the aluminum in solution which accelerates the precipitation rate. A similar test was made using 300°F. as the aging temperature and these results are given in Fig. 7. This figure shows the maximum hardness to be a function of the initial condition but that the rate of aging is practically the same for the three curves given.

Different runs were made on specimens that had been annealed at 775°F. for twenty-four, forty-eight, and seventy-two hours to deter-

[13] Teed, P. L., "Plastic Deformation and Age Hardening of Duralumin," Jr. of Institute of Metals, Nov. 1935.

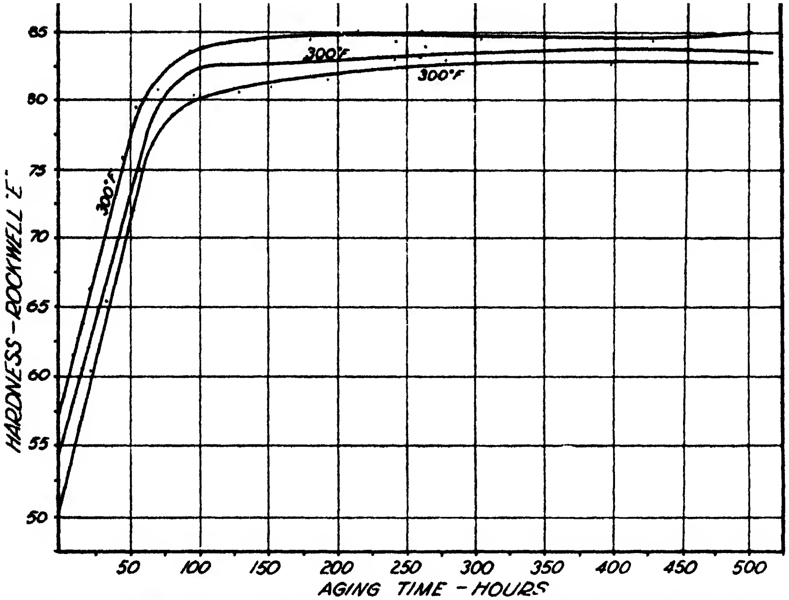


Fig. 7. Effect of initial hardness on 300° F. aging following partial anneal.

mine whether the time the specimen was held at the solution temperature after the minimum hardness was reached has an effect on either the rate of aging or the final hardness. These materials having approximately the same hardnesses but different annealing times showed no difference in aging characteristics as measured by hardness readings.

The micro-structure of a completely aged specimen was shown in Fig. 3C. This indicates that the increase in hardness accompanying the aging of this alloy is not explained by the theories that explain the behavior of duraluminum. In this case the atomic forces set up in the formation of the intermetallic compound Mg_3Al_2 but prior to its precipitation do not account for the hardness increase. Precipitation areas are observable very shortly after the beginning of aging and the hardness is proportional to the amount of this area present. The precipitated particles are not uniformly distributed throughout the metal but begin at the grain boundaries and form a definite laminated type of structure which Gann termed an embrittling eutectic.[12] The amount of this area present is greater than that indicated by applying

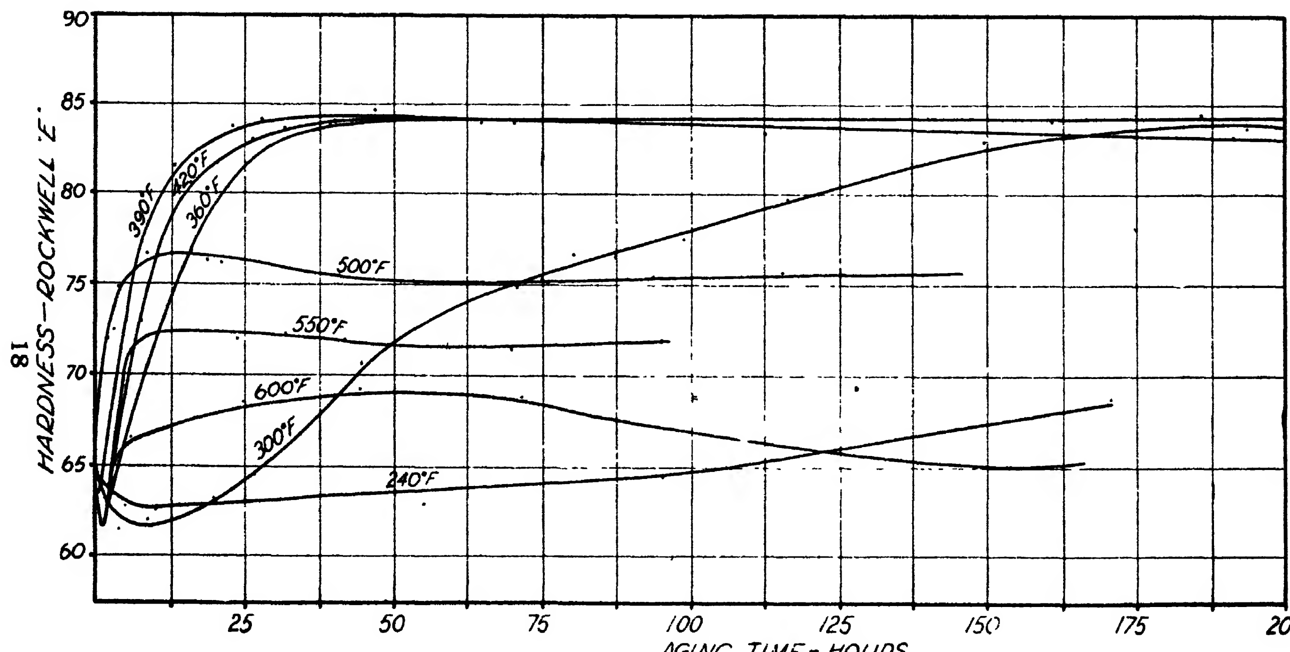


Fig. 8. Effect of temperature on aging of extruded material.

the lever relation to the equilibrium diagram for the determination of the percentage of eutectic that should be present. To account for the hardness increase this aggregate must be harder than the super-saturated solid solution of aluminum in magnesium.

VII. Aging from the Extruded Condition

Aging from the "as received" condition is possible because the extruded temperature was sufficiently high to give a super-saturated solid solution and precipitation at room temperature was not sufficient to produce any appreciable change in hardness. This aging gives a combination of strain anneal and precipitation hardening taking place simultaneously. A set of curves showing the effect of aging temperature on the rate and the final hardness attained is given in Fig. 8

Fig 8 shows that as for the case of aging from the annealed condition there is, for a given initial condition, a critical temperature which gives the maximum hardness in the minimum time This maximum hardness is the same as obtained by aging from a completely annealed state but a comparison of Fig 7 and Fig 8 shows that an aging time of only twenty-five hours is needed for the extruded material as compared to one hundred hours for the annealed material This shorter time may be attributed to the decreased power of the distorted

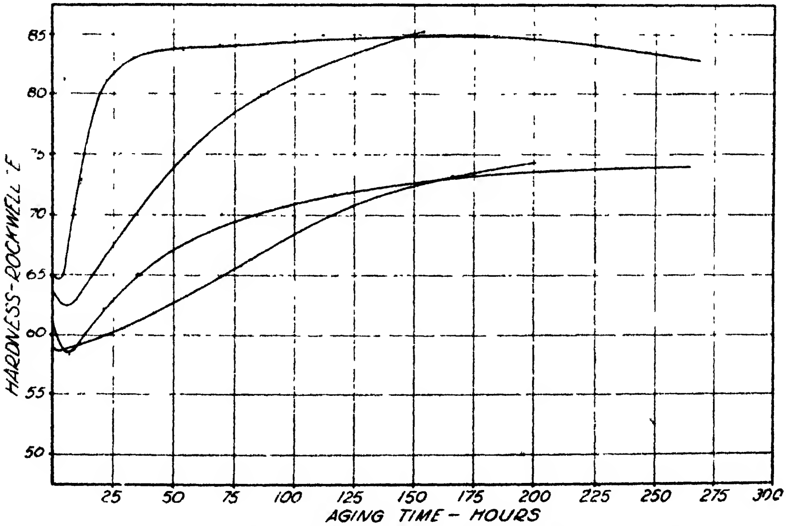
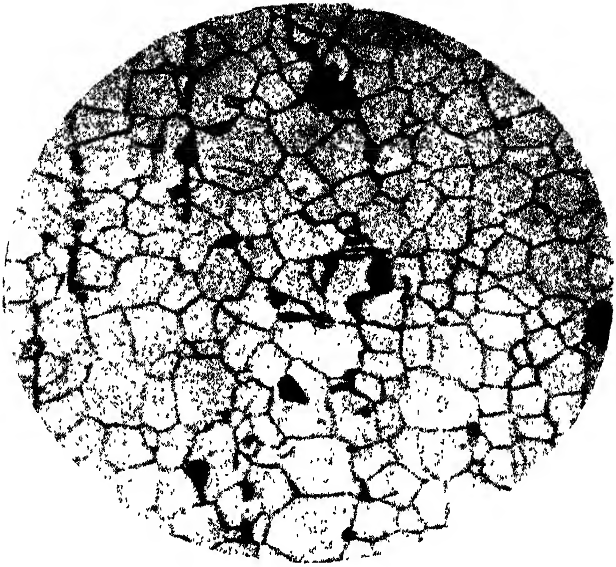


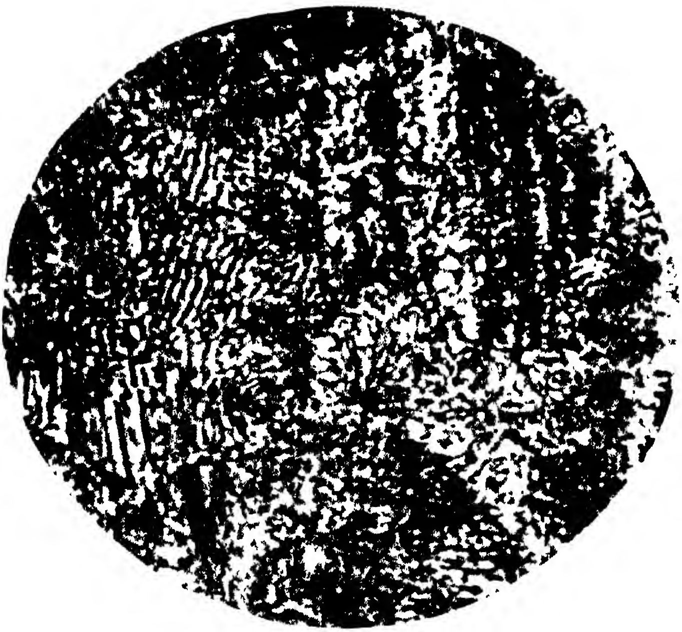
Fig. 9. Effect of initial hardness on 360° F. aging of extruded material.



A

B

Fig. 10. Microstructural changes accompanying 390° F. aging of extruded magnesium aluminum alloy (8% Al). Specimens A, B, and C show the increase in amount of precipitation with time and "D" shows an enlarged section of the precipitated structure.



D

lattice to retain the aluminum in solution. This effect of the amount of the initial strain on the aging characteristics is given in Fig. 9. These specimens which had different hardnesses due to extrusion have been all aged at 360°F. The combination of Fig. 8 and Fig. 9 show that for this case the aging rate as measured by change of hardness with time is a function of the initial condition as well as of the aging temperature.

The 300°F. aging curve of Fig. 8 is a good example of the combined effect of the strain anneal and precipitation hardening. With the beginning of heating the precipitation starts which would increase the hardness but at the same time the temperature is sufficiently high to cause some strain relief thereby promoting a softening effect

For the first ten hours the decrease in hardness due to strain relief is greater than the effect of increased hardness that would result from the aging alone. Beyond this time the hardness steadily increases, the precipitation effect being the predominating factor.

The steady increase in the size of the precipitated areas viewed on longitudinal sections of specimens that had been aged from the extruded condition 3½, 10½ and 16½ hours respectively at 390°F. is given in Fig. 10 These specimens were taken at 200 diameter magnification They were etched very lightly with a two per cent solution of oxalic acid. Structures A, B and C of Fig 10 show very strikingly the effect of hardness on the amount of precipitation and the gradual increase in the amount of precipitation from the beginning of the aging. Fig. 10C shows the laminated structure of the precipitated aggregate. This picture was taken at 800 diameters magnification.

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« « « PULLMAN, WASHINGTON » » »

Vol. 20 December, 1937 No. 7

Diversion Losses In Pipe Bends

Results obtained from tests of special conduit bends designed for lower fluid losses.

By Ellery R. Fosdick, E.E.
Engineering Staff
State of Washington
Department of Public Service
Olympia

ENGINEERING BULLETIN No. 51
ENGINEERING EXPERIMENT STATION
H. V. Carpenter, Director

PUBLISHED BY THE STATE COLLEGE OF WASHINGTON

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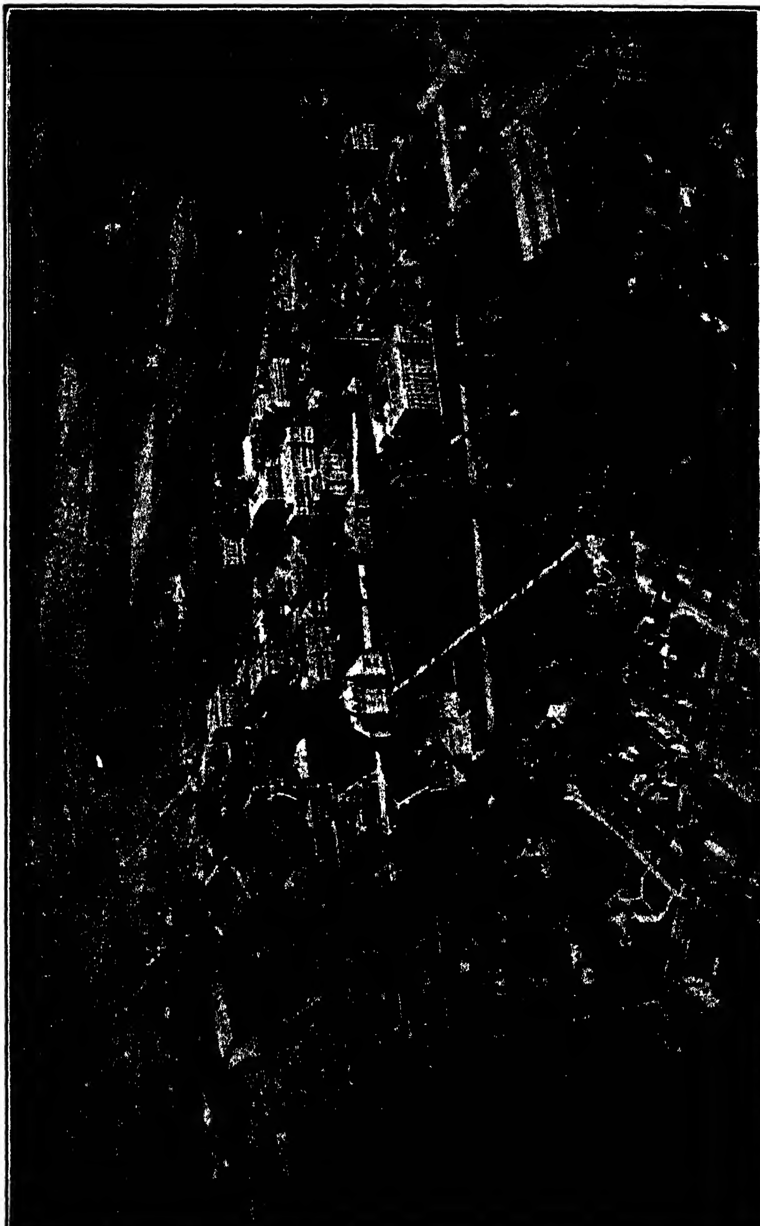


Airplane View of the State College of Washington Campus.

DIVERSION LOSSES IN PIPE BENDS

By

Ellery R. Fosdick, E.E.

INTRODUCTION

This bulletin is the culmination of investigations, tests and studies that were started by the author in 1929, when some field tests were made on the long flow line that conveys water from Lake Chelan, Washington, to the Chelan hydroelectric generating plant of the Washington Water Power Company. The results of these tests, which were subsequently published[1], indicated that the losses produced by the bends and the wye branch in the flow line were of considerably greater magnitude than were ordinarily supposed.

In view of the relatively large losses that resulted from the passage of the stream around the bends of the Chelan flow line, it was decided to investigate the matter further. During the fall and winter of 1933 the subject of losses resulting from bends in flow lines was investigated in considerable detail and it was found that virtually no work dealing with the general principles of the matter had been done.

Accordingly the author conducted some tests at the hydraulics laboratory of the University of Washington during the spring and summer of 1934 for the purpose of determining the nature of the losses resulting from a conduit bend. A report was prepared on this work and submitted to the University in the summer of 1934. Shortly afterward a number of investigators completed studies of a similar nature and some of these have been published.[2]

The nature of the losses as found by these tests made it seem likely that a change in the design of a bend would reduce the losses resulting therefrom. The various designs that might produce the desired results were carefully studied and some models which could be tested were constructed.

Numerous tests were made of various model bends in the hydraulics laboratory at the State College of Washington during the winter of

[1] "Tunnel and penstock tests at Chelan Station, Washington," by Ellery R. Fosdick, Transactions American Society of Civil Engineers, 1936, page 1409.

1935 and the summer of 1936. The laboratory facilities were made available for these tests by H. V. Carpenter, Director of the Engineering Experiment Station and Professor M. K. Snyder, head of the Civil Engineering Department. Professor J. G. Woodburn in charge of the hydraulics laboratory contributed much of his time and energy in assisting with the work that was done in the laboratory and it was largely through his efforts and cooperation that these tests were successfully completed. The work which was done in making these tests and the results obtained are presented in this bulletin.

THE REDUCTION OF LOSSES THAT RESULT FROM BENDS AND WYE BRANCHES IN FLUID CONDUITS

The science of fluid mechanics has been steadily improving through the years and during the last two decades extremely rapid progress has been made; but practically all of the mathematical formulae have been based upon empiricism. During the last few years this has been gradually changing through the use of dimensionless parameters such as the Reynold's Number. The use of Reynold's Number as a basis for comparison of hydraulic behavior in conduits of various sizes has been known since the last part of the nineteenth century and it seems strange that little use has been made of this valuable aid until recently.

The improvements which heretofore have been made in the science of hydraulics have been almost entirely in the field of dynamics and have usually been confined to such equipment as turbines, needle valves, draft tubes and intakes to flow lines. Practically no attempts have been made to improve the design and operating characteristics of such important parts of conduits as bends, elbows and wye branches.

The losses which result from bends and wye branches in conduits are fairly large and justify more consideration than has been given them in the past. They are of sufficient magnitude to warrant the expenditure of considerable sums of money in some cases in order to reduce them materially.

[2] "Flow of water around bends in pipes," by David L. Yarnell and Floyd A. Nagler, Transactions American Society of Civil Engineers, 1935, page 1018.
"Flow characteristics in elbow draft-tubes," by C. A. Mockmore, Proceedings American Society of Civil Engineers, Feb. 1937, page 251.

It is obvious that any improvements in the design of bends and wye branches must possess structural stability under high heads and at the same time must be economically justifiable.

The improvements which have been made to hydraulic structures, other than bends and wye branches, have reduced the losses occurring in them to such a low point that no material improvements can be expected in the future and therefore the only changes which are likely to be made are refinements which may result in very minor increases in efficiency. On the other hand, the designs of bends and wye branches have not, for the most part, been changed since the inception of conduits of circular cross section, and the losses in these structures are sufficiently large in some instances to justify the expenditure of considerable sums of money in order to improve the designs toward the end of increasing their efficiency and improving their operating characteristics.

GENERAL

In view of the foregoing facts, a considerable amount of research and investigation has been carried on by the author during the last few years to determine not only the character of losses that occur in bends and wye branches but also to determine, if possible, some means of reducing them with a structure so designed that it would be physically stable under high heads.

The passage of a fluid around a bend in a conduit results in a double spiral eddy in which the diversion loss occurs. This eddy is produced as a result of the distortion of the normal distribution of velocity and an abnormal pressure created by the centrifugal thrust of the fluid. These phenomena have been studied by several investigators and the results of their work have been previously made available to the engineering profession through the medium of various technical publications.[8] Consequently, no further discussion of the subject will be given here.

It has been known by hydraulic engineers for some time that the losses resulting from a bend may be materially decreased through the use of a conduit flattened in a plane at right angles to the plane of the bend. Such a structure, however, is suitable only for very low

heads and could not be made physically stable for high heads without an excessive cost.

In view of these facts, the selection of a design for reducing the losses in conduit bends would be more or less limited to a cross-sectional shape that was circular or some part of a circle, such that it would tend to maintain its normal contour under high pressures. After much investigation of this problem before starting these tests, it was finally decided to try a bend with a semi-circular cross section with the semi-diameter in the plane of the bend. Such a conduit might be easily constructed, for use under high pressures, from a circular pipe by merely installing a diametrical partition wall with relatively small vent holes in it which would transmit the fluid pressure to the side of the partition wall away from the moving column of water. In this way the hydrostatic pressure of the fluid would be exerted upon a physically stable structure with a circular cross section, while the dynamic flow would take place through a conduit having a semi-circular cross section and the partition wall would only have to withstand the forces produced by the dynamic flow of the fluid passing around the bend.

TEST EQUIPMENT

The tests that are described in this paper were conducted in the hydraulics laboratory at the State College of Washington, using a standard 6-in. pipe for the supply and discharge lines with a 90-degree test bend A schematic arrangement of the flow line which was used for these tests is shown in Figure 1 It will be observed that the supply line was a straight section of 6-in. pipe practically 33 ft. long, while the discharge pipe was a straight section of 6-in. pipe approximately 16 ft. long. The 90-degree test bends were inserted between these two sections of pipe (Fig. 2).

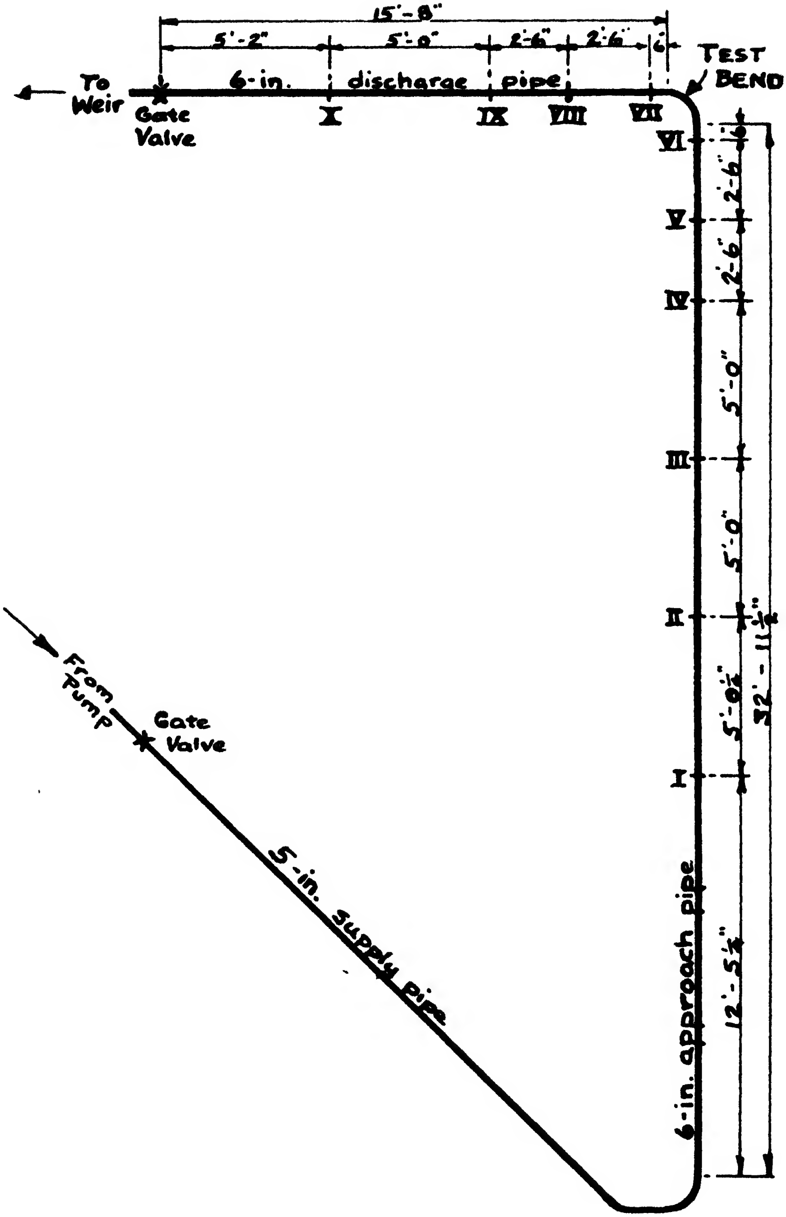
"Loss in 90-degree pipe bends of constant circular cross-section," by Albert Hoffmann, Transactions of the Munich Hydraulic Institute, Bulletin 3. (Translation by American Society of Mechanical Engineers.)

"Modern conceptions of the mechanics of fluid turbulence," by Hunter Rouse, Proceedings, American Society of Civil Engineers, Jan., 1936, page 21.

"Pressure losses for fluid flow in curved pipes," by G. H. Keulegan and K. H. Beij, Research Paper R P 965, National Bureau of Standards, Jan., 1937.

"Heat Power Engineering," Part III, by Barnard, Ellenwood and Hirshfeld, John Wiley & Sons, 1933.

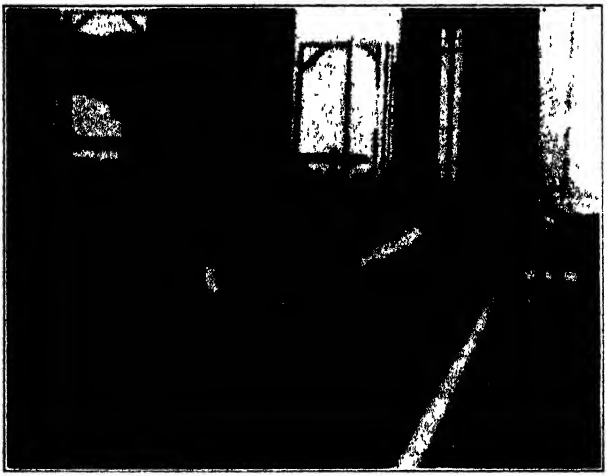
"Handbook of Hydraulics," by H. W. King. McGraw-Hill Book Co., 1929.


15'-8"
5'-2"
5'-0"
2'-6"
2'-6"
6
TEST BEND
To Weir
6-in. discharge pipe
Gate Valve
X
IX
VIII
VII
VI
V
IV
III
II
I
2'-6"
2'-6"
5'-0"
5'-0"
5'-0½"
12'-5¼"
32'-11½"
6-in. approach pipe
From Pump
Gate Valve
5-in. supply pipe

Supply line with Special Bend No. 1A in place. Standard Bend in foreground.

90-degree triangular weir used for measurements of flow through test bends.

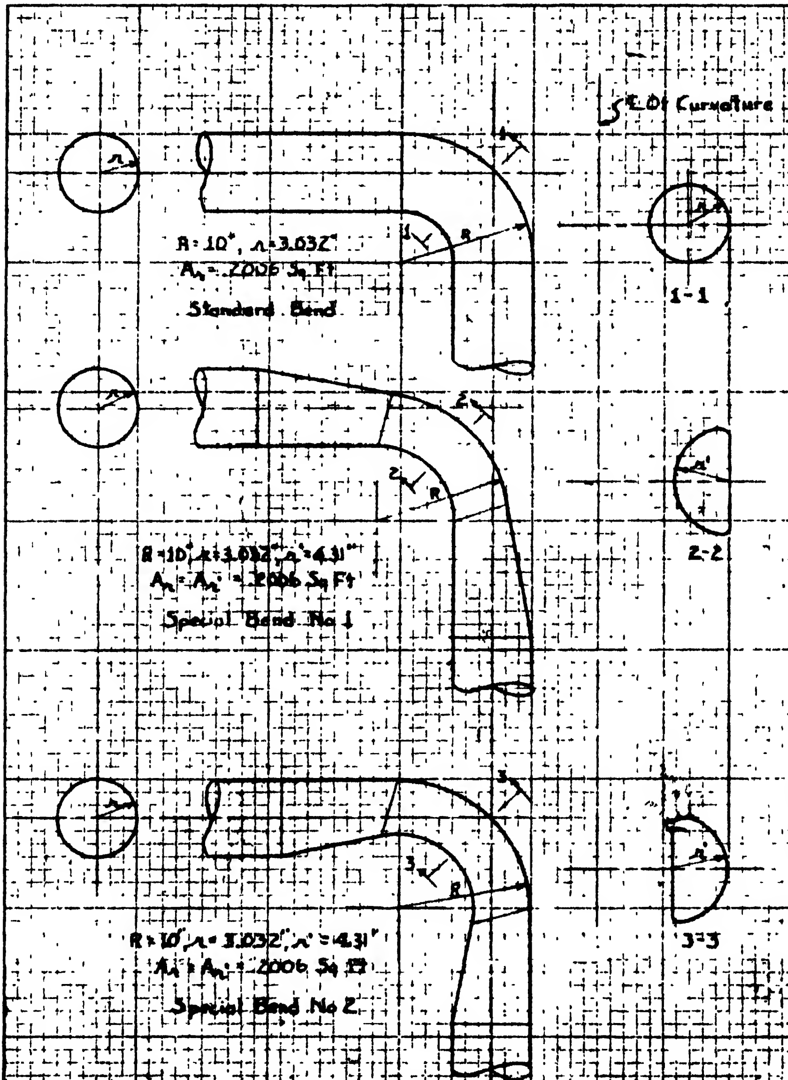
The water supply was obtained from a centrifugal pump and the flow was measured over a 90-degree triangular weir, shown in Figure 3, which had previously been calibrated within very close limits. The flow was regulated by means of a valve on the discharge side of the pump and the pressure on the flow line and test bend was regulated by means of a valve in the discharge pipe (Fig. 4).



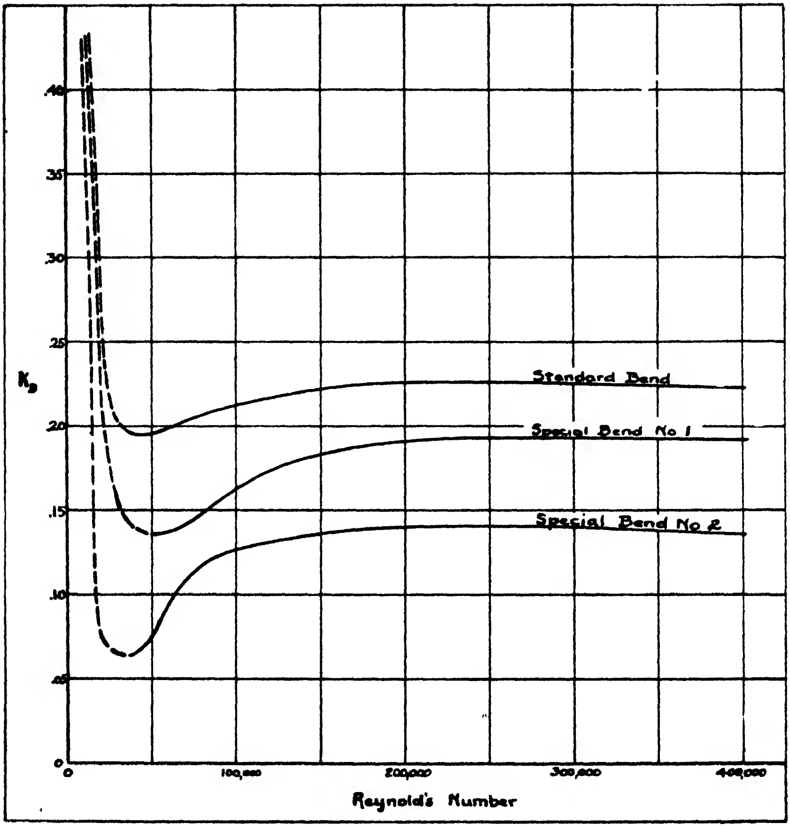
Discharge line and control valve. Test bend is near the wall.

Ten measuring sections were laid out along the 6-in. pipe as shown in Figure 1. At each of these sections were located four piezometers, spaced 90 degrees apart, on the top, bottom and sides of the pipe. Only the side piezometers were used in the readings. Each of the piezometers consisted of a 1/16-in. hole which had been drilled radially into the pipe and reamed with a specially built reamer so that the broken bits of metal were removed from the inside of the pipe at the edge of the hole and also so that the inside edge of the hole was slightly rounded.

Each of the piezometers was connected to a vertical glass-tube manometer. Throughout the tests of the first two bends, the oscillations of the water columns in the manometers were damped by pinching the rubber tubes that connected the manometers to the piezometers. During the tests on the third bend a 6-in length of capillary

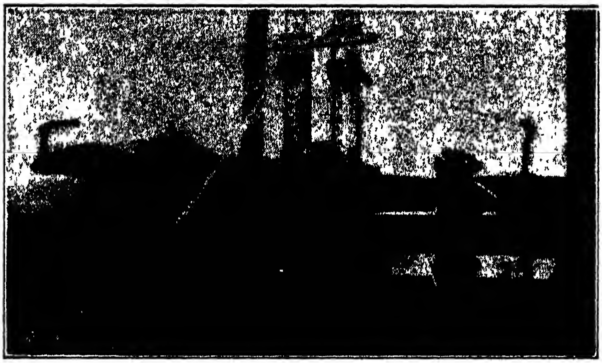


℄ Of Curvature
R = 10", r = 3.032"
A_r = .2006 Sq Ft
Standard Bend
1-1
R = 10", r = 3.032", r' = 4.31"
A_r = $A_{r'}$ = .2006 Sq Ft
Special Bend No 1
2-2
R = 10", r = 3.032", r' = 4.31"
A_r = $A_{r'}$ = .2006 Sq Ft
Special Bend No 2
3-3

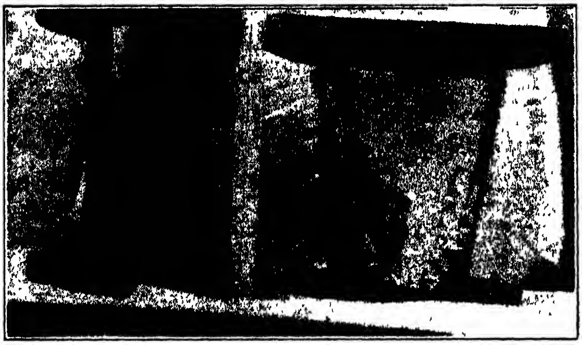


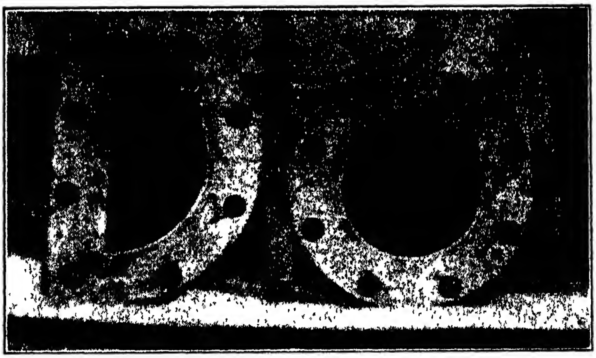
tube was placed in series between each manometer and piezometer for the purpose of damping the oscillations. The latter arrangement was found to be somewhat more satisfactory than the one originally used.

Three types of 90-degree bends were tested. The first one (See Fig 5) had a semi-circular cross section with the same area as a standard 6-in. pipe with the flat side of the semi-circular cross-section at right angles to the plane of the bend and on the side of the pipe away from the center of curvature. This bend, called Special Bend No. 1-A., was connected to the approach and discharge pipes by means



Special Bend No. 1A in place, showing flanged transition sections





Side and end views of flanged transition sections for Special Bend No. 1A.

Special Bend No. 1B in place. Flow approaches from top of picture.

of flanged transition sections as shown in Figure 6. Figure 7 shows the transition sections before assembly. After some preliminary tests had been run on this bend, another one was constructed and tested with the transitions and the bend cast integrally in one piece. This bend, called Special Bend No. 1-B, is shown in Figures 8 and 9.

The next set of tests was run on a standard 6-in. flanged, short-radius elbow. The third set of tests was run using a bend of semi-circular section similar to that used in the first series, except that the flattened surface was located on the side of the bend nearest to the center of curvature. This bend is called Special Bend No. 2 and is shown in Figure 10. All of the special bends tested had the same radius and curvature on the face of the pipe farthest from the center of curvature as the standard bend.

A total of 45 test runs, comprising 15,060 individual readings, were made of the friction losses and corresponding flows with these four bends. The results of these observations have been computed and graphically analyzed.

Front and rear views of Special Bend No. 1B in place.

Two views of Special Bend No. 2. This bend gave best results.

METHODS OF TESTING

It was found during the tests that the difference between manometer readings for right and left hand piezometers at any one station remained the same for any given rate of flow and for this reason it was unnecessary to take readings on both right and left hand manometers. Observation of pressure heads were, therefore, made in the manometers connected to the right hand piezometers only.

Twenty-five readings of the pressure head in the flow line were made for each condition of flow at each station in testing special bends 1-A and 1-B and the standard bend. The 25 readings were made at ten-second intervals and were found to cover at least one complete cycle of the variations in pressure present in the flow line under stable conditions of flow. Consequently, the average of these 25 readings for any one flow gave a fairly accurate measure of the average pressure head existing during the run.

In making the observations with special bend No. 2, the number of consecutive readings that was made for any one condition of flow was reduced to 20, as this number appeared to be adequate for the degree of accuracy desired. The method of reading and the interval of time between readings was the same as for the previous tests.

Due to the limited number of observers it was impossible to read all of the piezometers simultaneously, so it was necessary to take three groups of simultaneous readings for each test run at each of four adjacent stations. The stations which were read simultaneously in each group of observations had to overlap in order to determine a continuous hydraulic gradient for the entire flow line. That is, the last or fourth station in the first and second groups of readings was the first station read in the second and third groups of readings.

Observations of the flow were made by taking readings of the head on the 90° V-notch weir at thirty second intervals throughout each test run. The head on the weir was measured with a standard hook gage, with readings taken to 0.0001 ft. at the lower flows and to the nearest 0.0005 ft. at the larger flows.

The standard bend was tested under 15 different conditions of flow with a range of velocity from 2.5 to 7.2 ft. per sec. Special bends 1-A and 1-B were tested with a total of 21 different flows, having a range of velocity from 2.4 to 7.1 ft. per sec. and Special Bend No. 2 was tested for 9 different flows having a range of velocity from 1.7 to 7.5 ft. per sec.

COMPUTATION OF RESULTS

The average pressure head on the flow line at each station for each rate of flow was determined by averaging the right hand manometer readings and adding one half of the difference between the right and left hand piezometers to this average. Corrections for the elevation of the gage boards upon which the piezometers were mounted had previously been determined from a set of precise levels and these corrections were added to the average manometer readings so that the pressure heads would all be referred to the same datum plane.

The total losses in each section of the flow line were determined by subtracting the average pressure-head elevation at any station from that of the station immediately up-stream. Rating curves for each section of the flow line were constructed so as to show the losses for the various flows and for the different bends that were used in the tests It was found that the observed losses for the tests of any one type of bend fell in close proximity to the rating curve, indicating that the observations were fairly accurate.

The **total friction loss** of the flow line and bend, that is, the loss which would occur in a straight pipe of length equal to the combined lengths of approach pipe, bend and discharge pipes, was determined by using the rate of loss observed in the straight sections of pipe above and below points obviously affected by the bend, and applying this rate to the total length of the line.

The **total loss** in the flow line at any given rate of flow was taken as the sum of the losses in each section as determined from the rating curves. It was thus possible to determine rather accurately the total loss in the flow line within the range of velocities covered by these tests.

The **diversion loss** resulting from the fluid passing around the bend was found by subtracting the total friction loss in the flow line from the total loss in the flow line. It is recognized that a certain amount of error undoubtedly results from this procedure, but due to certain limitations upon the testing facilities, it was impracticable to directly determine the total friction losses in the flow line.

The temperature of the water used in the tests was measured at frequent intervals, in order to ascertain the kinematic viscosity. From

this factor, the mean velocity of the fluid, and the diameter of the pipe, it was possible to compute Reynold's Number for the various conditions of flow. This number affords a dimensionless parameter for designating the results of these tests so they may be transposed to other hydraulic structures having the same geometric similitude.

It will be observed from Figure 11 and Table I, which contain a summary of the information obtained in these tests, that the diversion loss factors for the standard and special bends approach a constant value at about R equals 250,000. This is in accordance with the observations of other investigators and indicates that the loss factors for a Reynold's Number of approximately 250,000 may be used with a fair degree of accuracy in computing the losses with a flow having a Reynold's Number many times greater.

No observations were made for a Reynold's Number much below 50,000 as this represents a very low mean velocity of flow for a pipe of this size and is a condition that is not ordinarily of importance in the operation of hydraulic structures, so while it may be of theoretical interest it is not of practical importance. It is probable, however, that if these observations had been made, the loss factor curves would have followed approximately the course indicated by the dashed lines on Figure 11.

CONCLUSION

The results of these tests as summarized in Fig. 11 indicate clearly that a considerable reduction can be made in the diversion losses that are produced by the passage of a fluid around a conduit bend through the use of bends having a semi-circular cross-section with the flat side at right angles to the plane of the bend. The semi-circular cross-section of the conduit bends that have been used in these tests creates a redistribution of the fluid velocity that minimizes the losses by reducing the unbalance of pressure resulting from the centrifugal thrust of the fluid column and by decreasing the resistance to flow around the bend on the side nearest the center of curvature.

The loss factors for special bend No. 1 with the flat side radially outermost were found to be materially less than the corresponding loss factors for a standard bend of circular cross-section having the same cross-sectional area and radius of curvature. The loss factors for

special bend No. 2 which had the flat side radially innermost were found to be much less than the corresponding loss factors for special bend No. 1.

The construction of a conduit bend having a semi-circular shaped passage for the moving fluid is feasible for operation under high-heads with the shell and partition design. In this type of structure a circular pipe having approximately twice the required cross-sectional area and designed to withstand the fluid pressure has a thin longitudinal partition wall that is secured in the pipe in a diametrical position in the plane at right angles to the plane of the bend. Relatively small holes in the partition wall transmit the fluid pressure to both halves of the conduit with the result that the only force acting on the partition wall is the relatively small pressure produced by the dynamic action of the fluid.

TABLE I

DIVERSION LOSSES IN PIPE BENDS

Summary of Loss Data

	Standard Bend		Special Bend No. 1		Special Bend No. 2	
$V^2/2g$	R	K_b	R	K_b	R	K_b
.0622	84,700	0.207	84,700	0.150	77,000	0.120
.249	170,000	0.225	170,000	0.187	154,000	0.137
.560	254,000	0.220	254,000	0.192	231,000	0.134
.995	339,000	0.231	339,000	0.202	308,000	0.141

The total diversion loss factor K_b is the sum of the diversion loss factors in the several sections of the flow line as they were obtained from diversion loss curves that were established for each section of the flow line. The diversion loss curves were plotted through the large number of points representing the observed diversion losses in each section of the flow line. They were drawn so as to represent an average of the observed diversion losses.

R = Reynold's Number

K_b = diversion loss factor in equation: Loss = $K_b \cdot V^2/2g$

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Physical Properties of Magnesium Alloys

No. 2--Physical Changes Accompanying High Temperature Annealing of a Magnesium Alloy

by James G. McGivern
Assistant Professor of Mechanical Engineering

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H. V. Carpenter, Director

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Physical Properties of Magnesium Alloys

No. 2--Physical Changes Accompanying High Temperature Annealing of a Magnesium Alloy

by James G. McGivern
Assistant Professor of Mechanical Engineering

ENGINEERING BULLETIN No. 52
ENGINEERING EXPERIMENT STATION
H V Carpenter, Director

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PHYSICAL CHANGES ACCOMPANYING HIGH TEMPERATURE ANNEALING OF A MAGNESIUM ALLOY

By James G. McGivern

Introduction

Magnesium alloys with their high strength, light weight, and ability to be cast, rolled and extruded are being increasingly used for structural purposes. These alloys having a specific gravity of 1.74 to 1.84 may be classed as the lightest of the commercially used metals. They are only two-thirds the weight of aluminum and only two-ninths the weight of steel For equal weights their strengths compare favorably with and, in some cases, surpass our best alloy steels.

The physical properties of magnesium may be altered by alloying it with small percentages of other metals The alloying elements most commonly used are aluminum, zinc, and copper, together with a small amount of manganese to increase their resistance to corrosion. By varying the percentages of these elements certain combinations of strength, ductility, and hardness may be obtained both for the cast and worked conditions It is also possible to control substantially the physical properties of certain of these alloys by heat treatment.

The purpose of this report is to present the results of a study of the effects of annealing treatments at various temperatures on the physical properties of an extruded magnesium alloy containing 8% aluminum and 2% manganese The data is presented by means of curves and tables The curves show the effect of time of heating at the various annealing temperatures on the maximum stress, yield strength (2% permanent deformation) hardness, per cent elongation in two inches, and the per cent reduction in area The tables give in addition the yield strength (1% permanent deformation) Johnson's limit, uniform reduction in area, true elongation in two inches, and the breaking strength on the basis of original area and on the basis of reduced area. A short explanation of the heat treatment used, definitions of the terms employed, and micro structures and fracture pictures are also included.

Principle of the Heat Treatment

The dark lines of Fig. 1 give the equilibrium diagram determined by Schmidt and Spetaler[1] and represent the magnesium rich portion of the magnesium aluminum series. The line a,b, indicates how the solubility of aluminum in magnesium varies from 11% at its final freezing temperature to 7% at room temperature. The line has a sharp break at 525°F., and shows that for the 8% aluminum alloy being investigated there is a temperature range of approximately two hun-

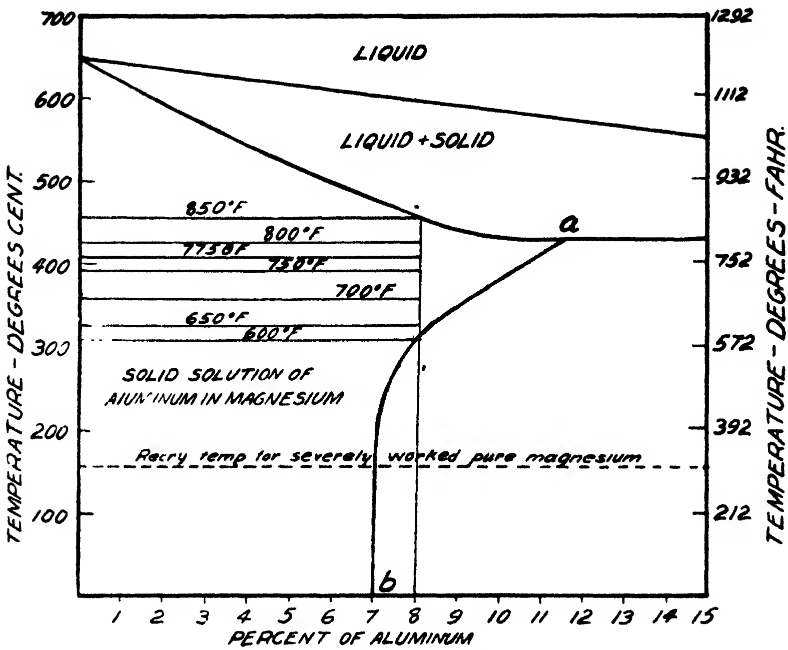

Fig. 1. Magnesium-rich portion of magnesium-aluminum series.

dred and fifty degrees between 600°F. and the beginning of melting where all the aluminum should, under equilibrium conditions, be in solid solution with the magnesium. These temperatures and solubilities are only to be taken as approximate as the exact nature of the curve has not been agreed upon by the numerous investigators work-

[1] Schmidt and Spetaler, Jr. Inst. of Metals, Vol. 38, p. 195.

Fig. 2. Difference in microstructure of rods having different initial hardness. Specimen A (65 Rockwell E) and B (69.-71 Rock. E). 100X

ing in that field.[2] It should also be remembered that diagrams similar to Fig. 1 are determined for equilibrium conditions and do not hold exactly for metals in the strained state.

The material as received is an extruded rod that was worked at a temperature sufficiently high to cause most of the aluminum to be in solid solution with the magnesium.[3] All the rods are not alike with respect to the amount of aluminum in solution or as to grain size. Figs. 2a and 2b give the micro-structure of longitudinal sections cut from two different rods in the as received condition. The precipitation for the one specimen is not so evident and is confined to the grain boundaries and along the inclusion stringers. The second specimen, Fig. 2b has considerable precipitation and a smaller grain size and has a hardness of 69 Rockwell E as compared to 65 for the other rod.

By anealing for various time intervals at temperatures between 600°F. and 825°F. as indicated on Fig. 1, one function of the annealing process will be performed. This consists in causing all the aluminum to be soluble in the magnesium and means the breaking up of the hard intermetallic compoung Mg_3Al_2 which formed with the previous pre-

cipitation of the aluminum at the grain boundaries and along inclusion stringers.

The other function is to relieve the metal of the effects of the strain hardening associated with the extrusion process. This is accomplished by heating at a temperature sufficiently high to cause new grains to become visible under the microscope which indicates a change from the strain hardened to the annealed state. The temperature of recrystallization is not a constant for each metal but becomes lower as the amount of previous cold working increases, as the temperature of the working lowers, as the metal becomes purer, as the grain size prior to deformation decreases and as the time of exposure at the temperature incraeses. The lowest temperature of recrystallization for severely plastically deformed pure magnesium is quoted as 302°F.[4] which is well below our lowest annealing temperature of 600°F. Grain growth accompanies recrystallization and is used along with the various tests to measure the degree of strain relief.

PHYSICAL TESTS AND MEASUREMENTS

For the determination of the tensile properties the standard two-inch gage length specimen having ,a 505 inch diameter was used.[5] Three-quarter inch fillet radii was found necessary to prevent failure at the ends and polishing with magnesium oxide was helpful.

The threaded ends of the specimens were screwed into spherically seated chucks which were fastened by wedge shaped grips to a 200,000 capacity Riehle screw machine. A loading speed of 022 inches per minute was used to failure. Strain readings corresponding to load increments of 150 pound loadings (750 lbs /sq.") were taken on a "Last Word" Olson extensometer having divisions representing one-fifteenth of a thousandth of an inch extension in the two inch gage distance.

The stress strain diagrams of magnesium alloys are characteristic of those of brittle materials and exhibit a smooth curve of gradual

[2] See for discussion- McGivern, J. G., and Wilkinson, C. A. "Precipitation Hardening of a Mg. Alloy containing 8% Al" State College of Wash., Eng. Exp. Sta. Bulletin 50, July, 1937.

[3] Gann, J. A. "Magnesium-Industries Lightest Structural Metal," paper presented at Western Metal Congress, San Francisco; Feb. 17, 1931.

[4] Jefferies, Z. and Archer, R. S., "Science of Metals," p. 86, McGraw-Hill Book Co., New York, 1924

[5] Proceedings of Am. Soc. of Testing Matrs. Part I, p. 967 (132); also see 1934 Book of A.S.T.M. Tentative Standards.

curvature at the region of yield as shown in Fig. 3. Materials of this type have no yield point in the sense that the yield point is that stress at which there occurs a marked increase in strain with little or no increase in stress. In the absence of this factor, and due to the extreme amount of time and number of accurate measurements necessary to determine the elastic limit, other methods for determining the safe working stresses are employed. The more commonly used of these are the yield strength, Johnson's limit and the stress corresponding to a specified total strain.

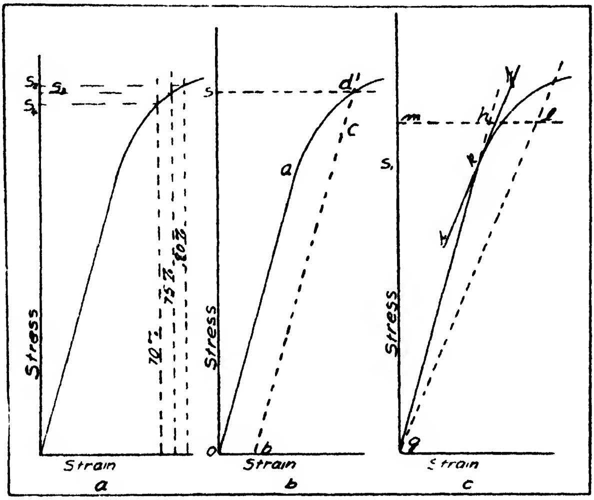

Fig. 3. Diagrams illustrating determination of yielding characteristics.

The Yield Strength is that stress at which the material exhibits a specified permanent set upon removal of the load The amount of this set corresponds to the value of plastic yielding above which there is danger and below which the effects may be considered negligible When the stress strain curve breaks away very gradually and shows no flattening tendency the yield strength will vary considerably with the amount of permanent set used In this work the stresses corresponding to a permanent set of 0 20 of one per cent and also of 0.10 of one per cent of elongation in the two inch gage length are reported with only the .20 per cent value represented on the curves. The actual determination of the yield strength is illustrated in Fig. 3b where "o,b" is the specified permanent set and "bc" is a line parallel to the modulus line "oa" and intersects the stress strain curve at "d" giving the yield strength represented by "S."

Johnson's Limit[6] is that stress where the rate of deformation of the material is 50% greater than it is at the origin. Fig. 3c shows the method of determining this

[6] Johnson, J. B., "Materials of Construction" 6th Ed., p 10, 1926, John Wiley and Sons, Inc., New York City.

value. The line "g,h" represents the slope of the modulus line at the origin and line "i,j" has a slope 50% greater than "g,h" and is tangent to the stress strain curve at "K" which gives Johnson's Limit. The line "i,j" is parallel to "g,l" which was drawn by making "m,l" equal to 1.5 of "m,h."

The Stress Accompanying a Specified Strain is the easiest value to determine and when once justified does not require the taking of stress strain values with the exception of the one strain and corresponding stress reading. The greatest value of this method is that many times it is possible to find a close correlation between this value and the yield strength which when once established reduces the time of testing. The stresses corresponding to strains of .70%, .75%, and .80% elongation have been recorded as these values are well up on the knee of the curve and appear to have value. These stresses are represented in Fig. 3a by S_4, S_3, and S_2 respectively.

The hardness values recorded are read on curved surfaces of the test specimens using the Rockwell E scale. These readings gave a sufficient range to insure good accuracy but may easily be converted to corresponding readings on other hardness scales.[7] The readings on the curved surfaces may be converted to corresponding readings on flat surfaces.[8]

825°F. and 800°F. Anneal

Oxidation. Referring to Fig. 1 shows the 825°F. temperature to be very close to the beginning of melting and unless provided for, excessive oxidation would take place. Covering the specimens with iron filings protected them so that no noticeable effects could be detected on the polished surfaces. A comparison between a few protected specimens (designated 1) and those exposed to the furnace atmosphere (designated 2) is given in Table I.

TABLE I

	Time in 825° Furnace	Hardness after Annealing	Hardness after Failure	Yield Strength .02% Set	Max. Stress	Per cent reduced in area	Per cent Elong. in 2"
1	4 Hrs.	61.0	76.4	25,800	43,000	28.10	23.0
2	4 Hrs.	57.5	74.7	30,750	44,600	17.70	17.0
1	7 Hrs.	59.8	76.2	27,200	43,950	22.80	17.85
2	7 Hrs.	58.9	76.0	28,500	44,300	15.40	14.0
1	10 Hrs.	60.8	75.9	28,800	44,500	19.40	16.3
2	10 Hrs.	56.6	72.0	43,600	43,600	11.75	12.0

[7] Petrenpo, S. N., "Relationships Between Rockwell & Brinell Number," Tech. Paper of Bur. of Std. No. 334, January 10, 1927.

[8] See for discussion—McGivern, J. G., and Wilkinson, C. A. "Precipitation Hardening of a Mg. Alloy Containing 8% Al." State College of Washington Eng. Exp. Sta. Bulletin No. 50, July, 1937.

Increase in Ductility with Beginning of Annealing. The changes in the physical properties accompanying various time anneals are given by the curves of Figs. 4 and 6 and by Tables II and III. These readings are for specimens that were protected against oxidation and quenched in water at 70°F. after having been held in the furnace the specified time. The time necessary for the specimens to come to temperature was twenty minutes. The initial hardness readings were those taken after quenching but prior to testing.

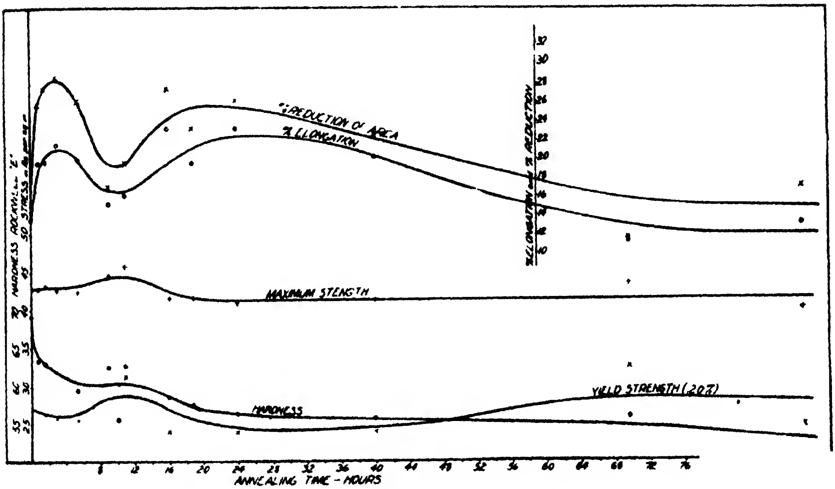

Fig. 4. Physical properties accompanying 825°F. anneal.

The curves of Fig. 4 and 6 show that there are some changes in the ultimate strength with time, and a greater change in the yield strength. The greatest changes are to be noted in hardness, percentage reduction of area and per cent elongation. For the 825°F. anneal and for the 800°F. anneal there is a decided increase in ductility in the first four hours and the first six hours respectively. The percentage reduction in area increases to 28% and the elongation to 21.5% for the 825°F. treatment while for the 800°F. anneal the respective values are 30.0% and 20.0%.

During this time two things are taking place. The first is the recrystallization of the previously extruded material. This recrystalliza-

TABLE II (825° F. Anneal)

No.	Time Hrs.	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	% Unif. Red.	% Unif. Elong.	.1% Yield Str.	.2% Yield Str.	John-son's Limit	.7% Yield	.75% Yield	.8% Yield	Max. Stress	Break-ing Stress	Stress on Final Area	Stress on Unif. Area at Max. Load
50	3/4	63.1	79.1	19.5	25.5	15	34	25100	26500	22250	26150	26750	27000	42600	40600	54500	50200
51	1:40	63.0	78.4	19.5	27.25	14.65	37.7	24900	26350	19000	23100	23600	23850	43000	40500	55300	50300
54	3:00	62.0	76.8	21.5	28.45	14.3	39.9	24500	25850	21250	25600	25900	26200	42500	39400	55100	49700
55	5:30	59.3	76.0	19.7	26.0	12.3	35	24500	25300	22000	25000	25250	25750	42300	41100	55400	49200
59	9:00	60.2	76.3	15.0	16.9	12.3	20.5	31250	32400	28750	32250	32600	33000	44500	44100	53200	50600
67	11:00	61.1	75.5	16.0	19.4	10.9	24	31250	32750	28000	31500	32250	32750	45800	44900	54700	51500
52	16:00	58.5	77.5	23.0	27.25	15.1	37.5	22500	23750	19000	23100	23600	23850	41400	40300	55200	48600
53	19:00	57.5	76.8	19.5	23.05	15.9	30	23500	25250	20750	25000	25500	25800	41500	39500	51300	49400
57	24:00	56.1	76.0	23.0	26.0	18.6	35	22500	23750	19000	22000	22750	23250	40800	40000	53900	50100
58	40:00	55.5	76.3	20.0	22.3	15.1	29.2	22250	23750	18000	23250	23650	24000	41200	40400	52400	48500
68	69:45	55.6	71.0	11.0	11.4	9.1	13	31250	32250	28250	31600	32000	32400	43200	43200	50000	48600
70	90:00	43.5	67.0	13.0	16.95	7.5	20.5	22800	24750	18500	25250	25750	26000	40000	38800	46800	43200

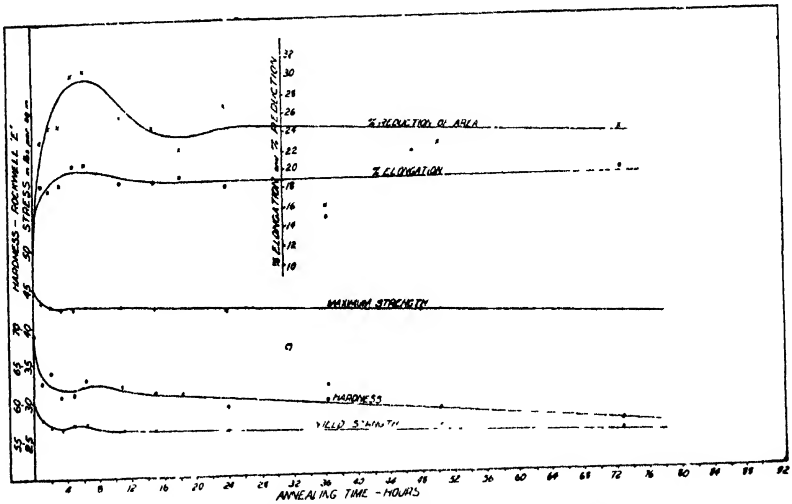

Fig. 6. Physical properties accompanying 800°F. anneal.

TABLE III (800° F. Anneal)

No.	Time Hrs.	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	% Unif. Red.	% Unif. Elong.	.1% Yield Str.	.2% Yield Str.	John-son's Yield	.7% Yield	.75% Yield	.8% Yield	Max. Stress	Break-ing Stress	Stress on Final Area	Stress on Unif. Area at Max. Load
31	1	62.9	71.5	19	23.7	12.8	31.0	26850	28000	24500	27250	27750	28000	43300	40500	53000	48900
32	2	64.1	75	18.5	25.2	13.3	33.5	25750	27000	23750	26750	27250	27750	42700	40400	54000	49300
33	3½	61	77.5	19	27.4	12.65	37.5	25750	26750	21500	26750	26850	27200	42500	41400	55700	49400
34	5	61.3	75	21	30.8	13.0	44.5	26150	27100	24250	26750	27200	27500	42500	40500	58500	49100
35	6½	63.1	76.5	21	31.2	14.6	45.2	26000	27250	22750	27000	27400	27850	42800	40600	59000	50100
37	11	62.2	77.4	19	26	12.8	35.2	25250	26400	22000	25800	26250	26600	42700	40200	54300	48900
43	15	61.3	77.5	19	24.8	7.8	33.5	24600	26250	22000	25500	26250	26500	42300	41600	55400	48700
38	24	59.3	76.2	18.5	27	12.7	36.5	25000	26100	21750	26000	26250	26500	41800	40500	54800	50200
41	36½	59.9	75	15	16.3	9.84	20	31000	32000	28250	30750	31250	31750	44900	44400	53000	49800
40	50½	58.4	77.3	19	22.6	14.2	29	24750	26250	19500	26500	26800	27200	41400	40300	52000	48300
42	73	56.6	76.5	19.5	23.9	12.6	31.0	24000	25250	21250	24850	25250	25500	41500	40600	53400	47500

tion is intimately associated with grain growth and the elimination of the directional characteristics of the alloy. Prior to annealing, this material, having a hexagonal space lattice with one plane of easy slip, has a preferred orientation and many directional characteristics common to a single crystal.[5] The second is the breaking up of the hard intermetallic compound Mg_3Al_2 and causing the aluminum to go into solid solution. The rate of solution anneal is dependent upon the rate of strain anneal as the author found the solution anneal of an aged specimen free from strain hardening to take ten minutes as compared to ten hours for a strained specimen.

Micro-structures and Dissolving of Precipitate. The visible disappearance of the precipitated particles during the first five hours of heating at 825°F. is clearly seen by referring to the micro-structures of Fig. 5. This change along with the strain relief associated with recrystallization would account for the initial increase in ductile properties

There was some difficulty in revealing the micro-structures after heating at these annealing temperatures This was due to the precipitated particles at the grain boundaries going back into solution first and making the etching ineffective. By reheating at 250°F. following the quench from the annealing temperature, sufficient reprecipitation took place to make etching with a 2% solution of oxalic acid effective The temperature 250°F is well below the recrystallization temperature and does not affect the grain size Except for anneals of five hours or more the reheating was not necessary to bring out the precipitated stringers but was used for grain boundaries only. The time of reheating varied from twenty minutes up to two hours depending upon the time and temperature of the previous anneal.

Recrystallization. The recrystallization taking place during this initial softening is evident for the 825°F anneal by referring to Fig. 5 which shows there to be decided grain growth, particularly after five and one half hours. In addition, for this same temperature anneal two cubes were cut from a ¾″ diameter rod in the received condition and two more from a rod that had been annealed 5¾ hours One of these cubes in each set was compressed in a direction parallel to its

[5] Schmidt, W., "Kristallstruktur und praktische Werkstoffgestaltung am Beispiel des Elektronmetalls." Zeitschrift fur Metallkunde, Vol. 25. Oct. 1933.

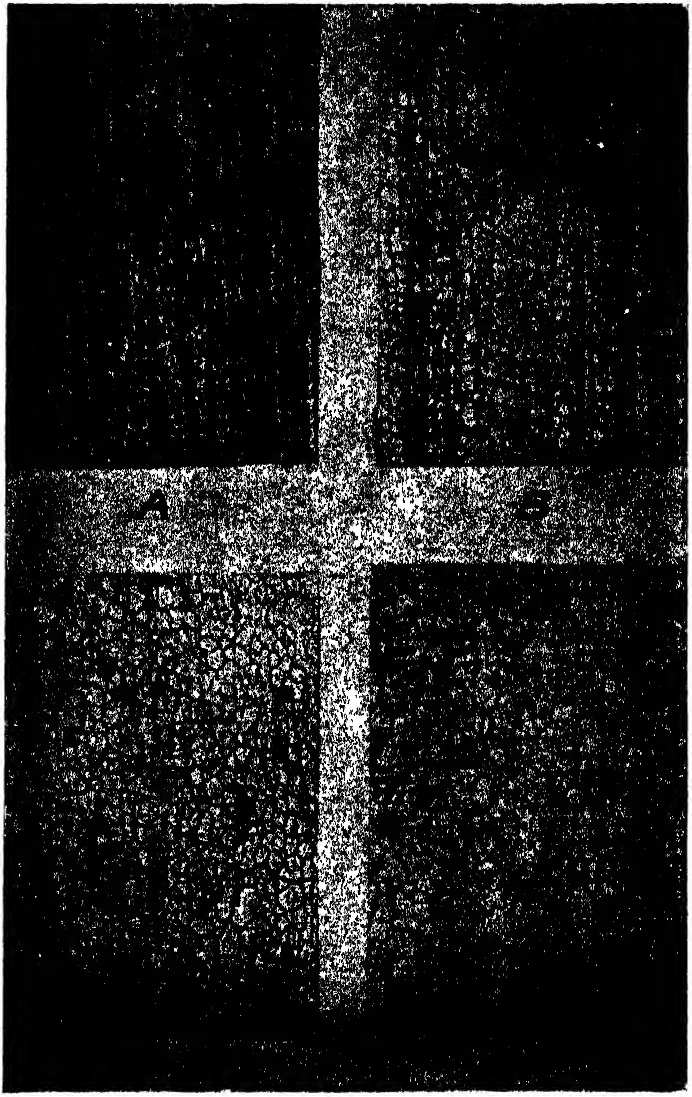

Fig. 5. Changes in microstructure for 825°F. annealing. Specimens A, B, C and D have been held at annealing temperature ¾ hr, 2 hrs, 5½ hrs, and 11 hrs. respectively. 100X.

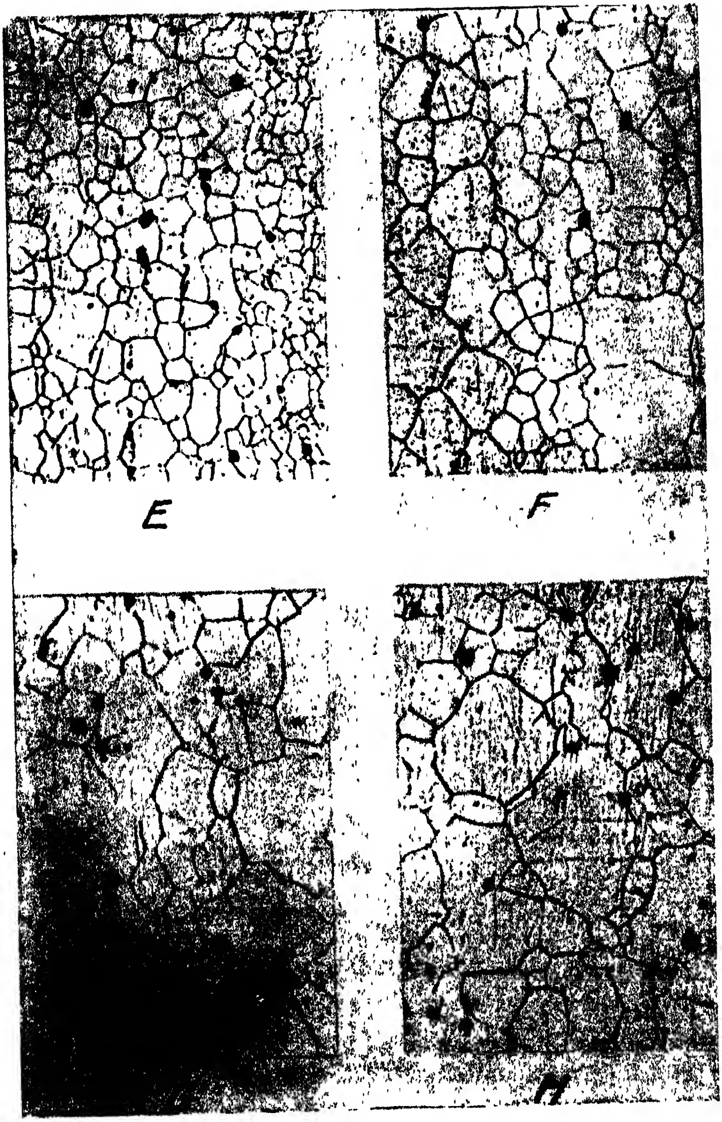

Fig. 5. Changes in microstructure for 825°F. annealing. Specimens E, F, G and H have been held at annealing temperature for 16 hrs, 19 hrs, 40 hrs, and 90 hrs. respectively. 100X.

axis and the other two were compressed perpendicular to the original rod axis. For the two untreated cubes the modulus of elasticity for the parallel direction was 1.45 times greater than for the perpendicular compression. The annealed set showed no such difference, the two stress strain curves practically coinciding. The yield strength (.20 set) for the untreated set gave 23,400 lbs./sq." for the parallel direction and 19,350 lbs./sq." for the perpendicular direction. By using the modulus line of the parallel compression test to determine the yield strength for the perpendicular test the value of 19,350 lbs./sq." would be replaced by 9,000 lbs./sq." The yield strengths of the annealed cubes were 16,550 lbs./sq." for the parallel specimen and 14,600 lbs./sq." for the perpendicular one. The modulus lines for these specimens were but 12% lower than for the lowest of the original specimens.

Ductility Changes Following Initial Rise. Reference to Figs 4 and 6 shows the initial rise in ductile characteristics to be followed by a drop which goes through a minimum at from nine to eleven hours A decrease is to be expected with increased grain size but the dip is not clearly understood. This dip is more pronounced for the 825°F. and 800°F. anneals than for lower temperature ones. It is also more pronounced for the per cent reduction in area than for the per cent elongation in length. Fig. 5 shows that for the first part of the dip there is a gradual increase in grain size with all grains growing at the same rate. This mechanism of grain growth does not continue, as from then on the slightly larger and more stable grains absorb the smaller ones. This results in a mixed grain size until at ninety hours practically all the originally uniform sized grains have been absorbed and the structure again presents a relatively uniform appearance. This, however, can hardly account for the decided changes given in Figs. 4 and 6. More work is to be done on this part of the curve and if it can be assumed that the mechanism by which the precipitate goes back into solution is the inverse of the precipitation phenomenon, then Fig. 2 of the work of Cohen[9] on the precipitation of a silver rich alloy may aid in understanding the problem. Both the magnesium aluminum and the silver coper alloys exhibit the same aging characteristics with the exception of the incubation periods. The aging of

[9] Cohen M., "Aging Phenomena in a Silver Rich Copper Alloy," Trans. of Am. Inst. of Min. & Met. Eng., Vol. 124, 1937.

these systems are best explained by a combination of the knot and precipitation theories.

Ultimate and Yield Strengths. Tables II and III give many measures of ductility, yielding, and failure which are being recorded here as a matter of record. They will be correlated in a later bulletin with the same properties corresponding to higher hardness values, thereby giving a larger range and making relationships more significant. The meaning of all of the items recorded are evident with the possible exception of items 7 and 8

Item 7 refers to the percentage reduction of the diameter removed from the finally localized necked section and is the per cent reduction of the uniform section at the maximum strength and just prior to the necking. This makes possible the determination of the true stress corresponding to the maximum load. Item 8 gives the per cent elongation associated with a specimen having a uniformly reduced diameter equal to the small diameter measured at the small end of the necked section.

The relative values for the strengths at failure and at yielding for the two temperatures are given by comparing Fig. 4 and Fig. 6. Following the first few hours these values remain practically constant for the 800°F. anneal, but the higher temperature shows more irregularity. For the 825°F anneal the yield strength is 67.2% of the maximum with a mean deviation of 6.17%. For the 800°F. treatment the yield strength is 63 7% of the maximum stress with a mean deviation of 1.67%..

Compressive Strengths. For the 800°F. anneal, compression tests were made on three-quarter inch diameter specimens having lengths equal to three times their diameters, their yield strengths averaged 66% of the yield strengths in tension of specimens subjected to the same heat treatment. Their maximum strengths were 150% of the maximum strengths in tension, and the failures were in all cases shear failures.

Fractures. The types of fractures obtained after testing specimens subjected to the 800°F. anneal for various times are given in Fig. 17. These specimens vary, some being practically pure shear failures and others show a combination shear and tension break. These latter are

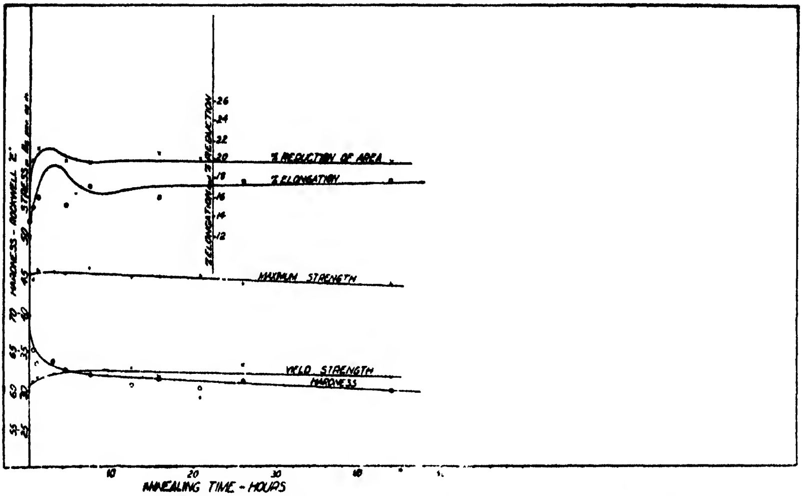

Fig. 7. Physical properties accompanying 775°F. anneal. (initial hardness 69).

TABLE IV (775° F. Anneal -- Initial Hardness 69 Rockwell B)

No.	Time Hrs.	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	% Unif. Red.	% Unif. Elong.	.1% Yield Str.	.2% Yield Str.	John-son's Yield	.7% Yield	.75% Yield	.8% Yield	Max. Stress	Break-ing Stress	Stress on Final Area	Stress on Unif. Area at Max. Load
1	0	69.0	78.4	13.5	11.95	10.2	14	29500	30750	26500	32000	32300	32750	45000	43300	49200	50000
2	½	65.1	77.6	15.0	19.9	19.3	24.5	29100	31250	27000	32100	32500	32850	44400	42400	53000	55000
26	1	63.6	78.0	16.0	21.0	11.2	26.5	30850	31750	28500	31250	31750	32300	45600	44200	56000	51400
3	1½	64.6	73.5	16.0	21.3	10.2	27.0	30500	31250	29000	31200	31750	32150	44600	44300	56300	49700
4	3	63.8	79.3	19.0	20.9	13.6	26.5	30000	32100	27000	32250	32750	33000	45200	43500	56200	52400
5	4½	62.7	75.0	15.0	19.9	10.2	25.0	28250	29400	25500	28500	29000	29500	45000	43900	54800	50000
12	7½	62.0	77.5	17.0	19.6	12.3	24.5	31850	32750	28250	31750	32250	32500	45700	44600	55500	52100
13	12½	60.8	74.5	16.5	17.2	12.6	23.5	31250	33000	28500	32500	33250	33750	44800	43500	54000	51500
6	15-3/4	61.5	77.0	18.5	20.6	12.2	26.0	31250	31800	28750	31150	31350	31700	44500	43800	55100	51200
8	20-3/4	60.2	70.8	16	20	11.3	25.0	28750	29000	27100	28800	28850	29000	44700	43900	54900	50500
11	26	61	79	17½	17.3	12.2	21.0	32250	33250	29650	32250	32750	33200	44500	43700	52900	50600
14	44	59.9	77.2	17.5	19.5	15.2	24	31600	31850	30000	32250	32500	37750	43600	43100	53500	49700

characterized by a large shear lip on the outside which is seldom completely round to give a typical cup and cone type of fracture. On the extreme ends are compression specimens which show a pure shear failure. The maximum strength in all cases appears to be dependent upon the shear strength.

775°F. Anneals

Comparing Fig. 7 and Table IV with Fig. 8 and Table V, the effect of initial hardness on the annealing at 775°F. is illustrated. Figs. 2a and 2b show the difference in micro-structures of these two materials.

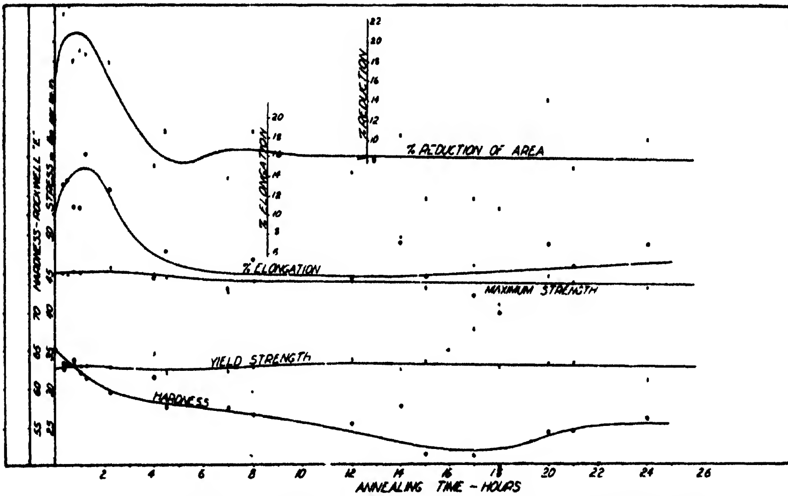

Fig. 8. Physical properties accompanying 775°F. anneal. (initial hardness 65).

TABLE V (775° F. Anneal -- Initial Hardness 64.5 Rockwell E)

No.	Time Hrs	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	% Unif. Elong.	.1% Yield Str.	.2% Yield Str.	John-son's Yield	.7% Yield	.75% Yield	.8% Yield	Max. Stress	Stress on Final Area
48	20 min.	64.2	75.1	17.2	23.3	30	31350	32650	28250	31250	31750	32250	45000	58600
49	½	63.3	75.5	17.6	24.1	32	32500	33250	28500	32250	32650	33000	44700	57800
44	3/4	63.9	72.0	14.8	18.2	22.7	32500	33400	28250	32000	32600	33000	45200	55200
45	1	62.1	73.8	14.8	19.2	24	31750	33000	29250	31500	32250	32750	45050	54000
46	1½	61.4	74.8	20.3	18.8	23.5	32000	33000	28000	31750	32250	32750	45100	53300
41	2½	59.4	74.2	16.5	17.8	27.7	31750	32900	29000	31750	32300	32750	45800	55200
28	4	61.7	71.6	7.5	7.1	7.5	33100	34500	29750	30250	31750	32650	44700	48100
31	7	57.4	67.4	6½	5.9	7.5	32250	33250	30000	31850	32500	33000	42400	45100
32	8	56.5	70.6	9.35	10.6	12	31750	32750	28000	31500	32000	32500	43800	49100
36	12	55.2	64.4	7.4	6.4	6.9	32000	33200	29750	31750	32500	33000	43600	46500
38	14	57.6	68.9	11	10.2	11	31000	32500	28250	31000	31600	32100	44500	49600
20	15	51.2	65	7½	3.5	6	31750	33400	28750	32000	32350	32850	42800	45500
22	17	51.1	60.2	5.5	3.6	3.5	36500	37750	33000	35250	36250	36850	45800	47600
39	18	49.4	62.6	3.9	2.4	2.5	31500	32850	28500	31000	31850	32500	40800	41800
68	20	54.1	73.7	11	13.9	16	31000	33250	27750	27000	28250	29500	44400	51450
26	21	54.1		8½	6.8	7.6	32250	33200	28750	31600	32250	32500	43500	46600
47	24	56	69.8	10.9	9.5	10.5	29500	31000	26500	29500	30000	30750	42900	47400

Fig. 8 which represents the annealing of a specimen of relatively low initial hardness (65 Rockwell E) shows a peak in the per cent reduction in area and per cent elongation which occurs with only one-half hour of heating as compared with the four and six hours needed for the 825°F. and 800°F. treatments and two hours for the

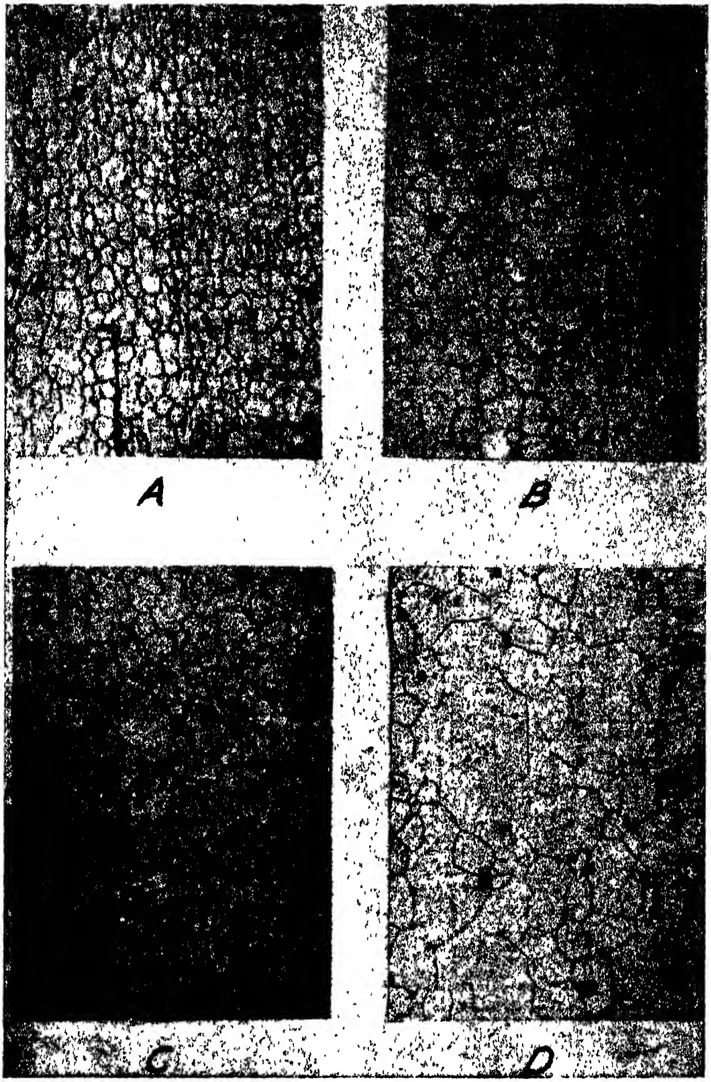

Fig. 9. Changes in microstructure for 775°F. anneal. Specimens A, B, C, D had initial hardness of 69. to 71. Rockwell E and were held at annealing temperatures 4½ hrs, 48 hrs, 79 hrs, and 216 hrs respectively. 100X.

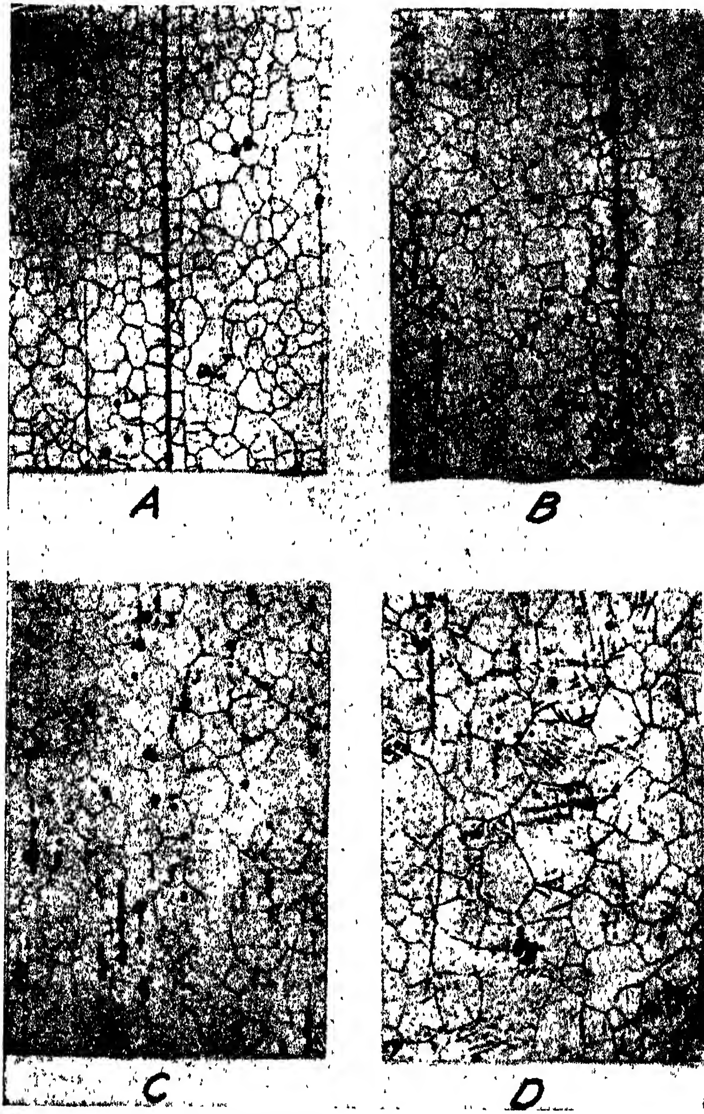

Fig. 10. Changes in microstructure for 775°F. anneal. Specimens A, B, C, and D had initial hardness of 65. Rockwell E. and have been held at annealing temperature o hrs, 3 hrs, 6 hrs, and 40 hrs respectively. 100X.

775°F. for material represented by Fig. 2b. The short time necessary is due to the relatively small amount of precipitate that needs to be dissolved as compared to the amount pictured in Fig. 2 for the material whose annealing characteristics are given in Fig. 7. Fig. 8 shows more of a dip in the ductility curves than does Fig. 7.

The maximum stresses and yield strengths do not vary a great deal with time. In the material of Fig. 7 the yield strength equals 70.4% of the maximum with a mean deviation of 2.26%, while for the other material the percentages are 73.3% and 2.1%.

The grain growth for these two materials is illustrated in Figs. 9 and10. The actual increase in size of grains with time is given for all the anneals in Figs. 11a and 11b.

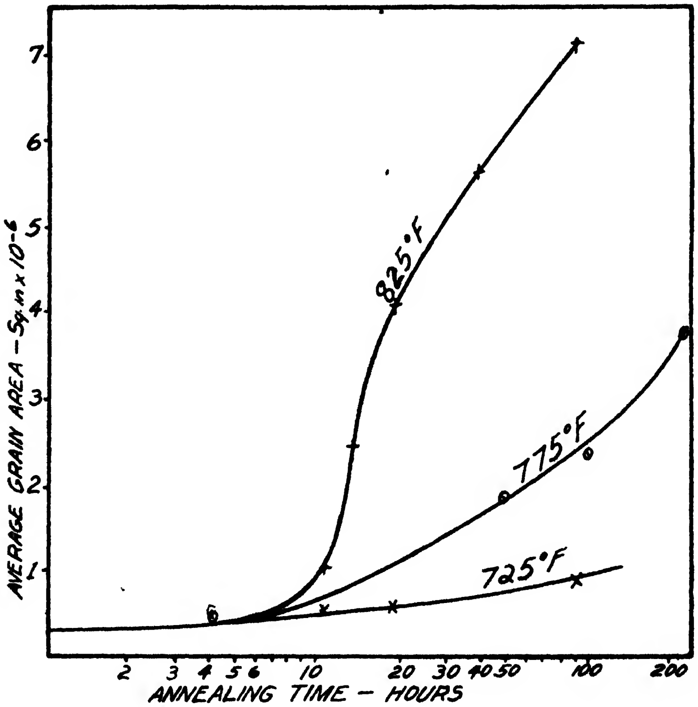

Fig. 11a. Grain growth as influenced by annealing time.

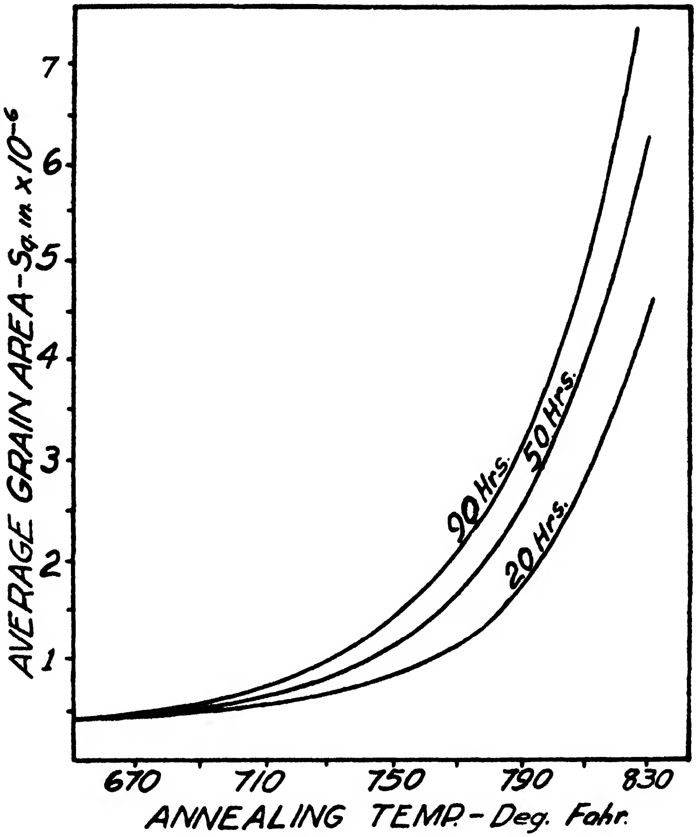

Fig. 11b. Grain growth as influenced by annealing temperatures.

725°F. and 675°F. Anneals

The changes in physical properties corresponding to these annealing treatments are given in Figs. 12 and 13 and in Tables VI and VII. The initial increase in ductile properties are similar to those for the previous heat treatments but the reduction following this first rise is much more gradual than in the previous tests. The dip is not evident for the 725°F. anneal but for the 675°F. treatment the area reduction does show some dip, but the per cent elongation has but a slight dipping effect.

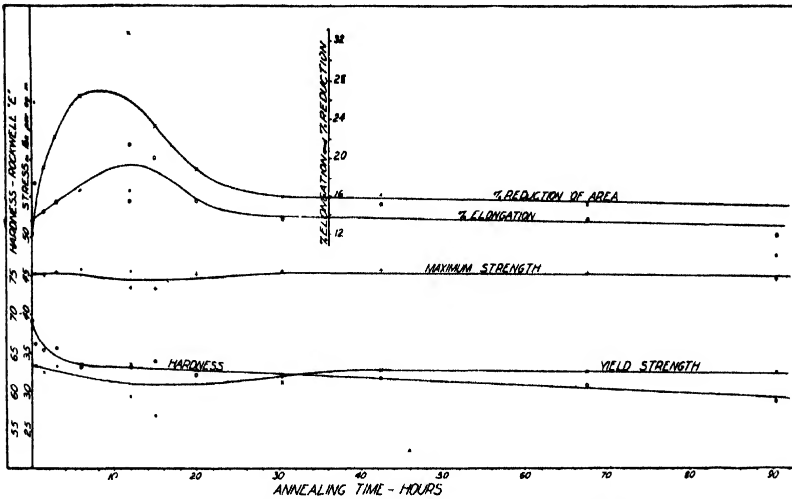

Fig. 12. Physical properties accompanying 725°F. anneal.

TABLE VI (725° F. Anneal)

No.	Time Hrs	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	% Unif. Red.	% Unif. Elong.	.1% Yield Str.	.2% Yield Str.	John-son's Yield	.7% Yield	.75% Yield	.8% Yield	Max. Stress	Break-ing Stress	Stress on Final Area	Stress on Unif. Area at Max. Load
73	½	66.2	77.4	17.5	25.95	12.4	34.5	32250	33250	29250	31750	32300	33250	45100	43800	59200	51500
74	1½	65.3	75.4	14.5	18.5	9.85	23.5	31350	32500	28000	31500	32000	32500	45000	44100	54400	49800
76	3	65.5	77.8	15.5	22.3	10.9	28.5	32250	33250	29500	32250	32750	34200	45400	43600	56100	51000
75	6	63.4	76.7	16.5	26.65	13.3	36.5	32350	33250	29500	32250	32750	33000	45700	44500	60800	52000
77	12	63.4	80.0	16.5	15.4	12.9	18.0	32250	33150	29500	32250	32650	33000	45400	40800	48100	52000
84	12	64.4	77.8	21.5	33.4	12 1	50	28500	29150	25250	27850	28500	28750	43200	39800	60000	49200
86	15	63.9	79.1	20.0	23.15	11.7	30	25750	26750	22500	26650	27000	27400	43000	39200	51000	43000
78	20	62.0	76.7	15.5	18.9	11.4	23	32250	32850	29500	32600	32850	33250	45000	44000	54000	51000
85	30½	61.9	74.4	13.5	15.8	11.3	18.5	29150	30100	26500	29650	33000	30250	45300	43200	51300	51000
87	42½	61.6	75.3	15.0	16.05	10.2	19.0	31400	32600	28500	31400	32000	32300	45400	43100	51400	50500
88	67½	60.7	72.9	13.5	15.0	10.1	18.0	31250	32480	28800	31300	32000	32480	45000	45000	53000	50200
89	90½	58.7	73.7	12.0	10.7	9.4	12.0	32500	32500	27750	31900	32250	32750	44500	43900	49100	49100
101	117	59.2	75.1	14.0	15.95	10.2	19.0	31150	32500	28000	31250	31800	32250	44900	44900	53500	50100

The changes in micro-structures accompanying the 725°F. anneal are given by Fig. 14. In this case the time of complete recrystallization is delayed because of the lower temperature employed and the rate of dissolving which is dependent upon the strain relief is also delayed.

Fig. 11 shows the slow rate of grain growth associated with this treatment as compared with those obtained for the high temperature anneals.

The average yield strength (.20%) for the 725%F. temperature is 71.7% of the maximum stress with a mean deviation of 3.2% while

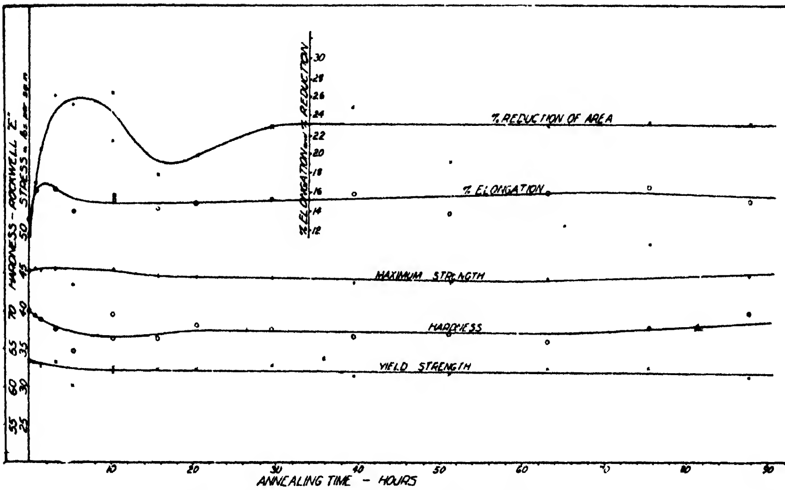

Fig. 13. Physical properties accompanying 675°F. anneal.

TABLE VII (675° F. Anneal)

No.	Time Hrs.	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	% Unif. Red.	% Unif. Elong.	.1% Yield Str.	.2% Yield Str.	John-son's Limit	.7% Yield	.75% Yield	.8% Yield	Max. Stress	Break-ing Stress	Stress on Final Area	Stress on Unif. Area at Max. Load
62	½	69.2	80.0	16.5	17.5	10.55	29	32500	33500	29250	33100	33500	33750	45600	44400	57200	50900
63	1¼	68.7	80.0	17.0	20.8	10.75	26	31750	32750	29500	31600	32150	32500	45000	43700	55200	50400
64	3:10	67.5	77.0	16.5	26.4	10.2	36	32250	33200	29000	32250	32750	33200	45300	43600	59400	50400
66	5	64.7	76.5	14.5	25.5	13.1	34.5	29150	30000	26500	29000	29350	29750	43200	42800	57500	50800
71	10	66.3	78.2	16.0	26.65	11.4	36	31750	32700	28250	32000	32500	32750	45100	43200	58800	50900
81	10	69.5	78.4	15.5	21.8	9.95	27.5	31000	32000	28250	31000	31500	32000	45000	42100	55200	49900
61	15½	66.3	77	14.5	18.1	10.2	22.2	31150	32250	27750	31700	32200	32500	44500	43500	53100	54500
65	20¼	66	76.5	15.0	20.2	9.25	25	31500	32250	29500	31250	31600	31900	44200	43100	54000	48800
69	29¼	67.4	76.6	15.5	23.1	11.2	28.5	32150	32750	29500	32200	32600	32750	44100	43100	56000	49500
72	39¾	66.4	76.5	16.0	25.2	9.25	33.5	30800	31300	29000	31000	31250	31400	43500	41500	55500	48200
79	51	61.8	75.2	14.0	19.3	10.6	24	30800	31750	28000	31200	31500	31850	43500	42500	52700	48600
80	65	65.8	76.4	16.0	23.0	10.1	30	31500	32250	29750	30750	31250	31600	44000	42500	55200	48900
82	75¾	67.4	77.6	16.5	23.4	13.95	32.3	30750	32250	26000	31000	31600	32000	43200	41500	54900	50200
83	87½	69.1	78.8	15.0	23.2	10	30.5	30000	31000	27250	30400	30750	31250	44300	42200	55000	49200

the corresponding values for the 675°F. anneal are 72.25% and 1.22%.

650°F. and 600°F. Anneals

Referring back to Fig. 1 it is seen that these temperatures are but slightly above the solid solubility curve and are border line cases between the case of solution treatment and aging.

Fig. 15 and the Table VIII give the changes for the 650°F. treatment and show softening to take place with a very gradual increase in per cent reduction in area and percentage elongation The maximum

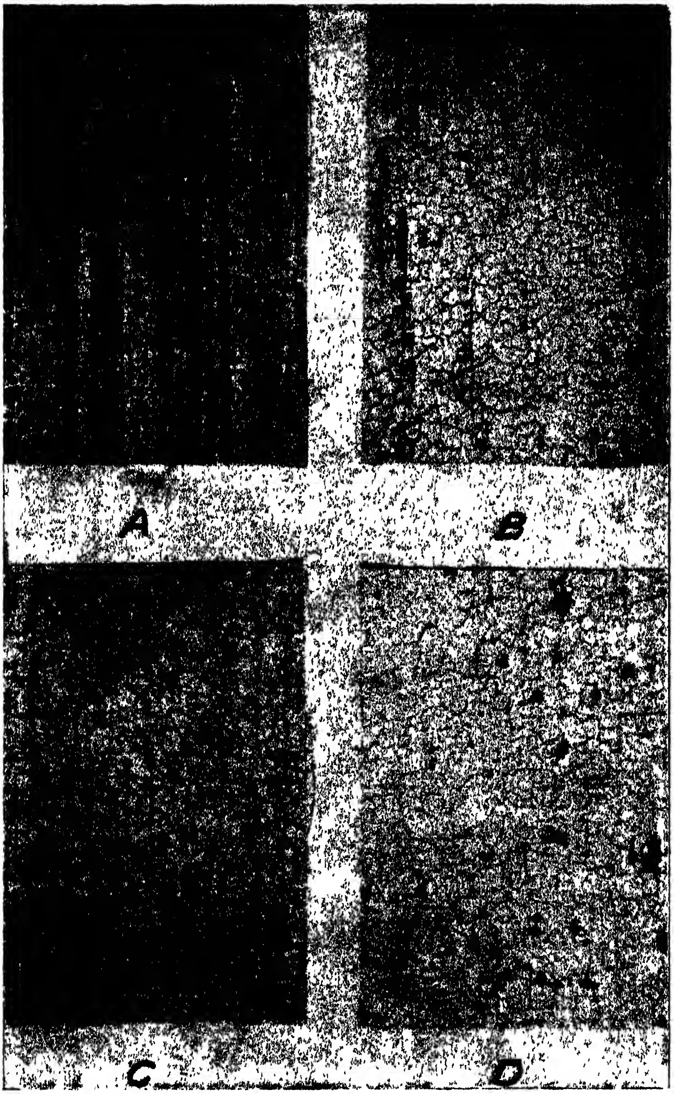

Fig. 14. Changes in microstructure for 725°F. annealing. Specimens A, B, C, and D have been held at annealing temperature 6 hrs, 20 hrs, 42½ hrs, and 90½ hrs respectively. 100X.

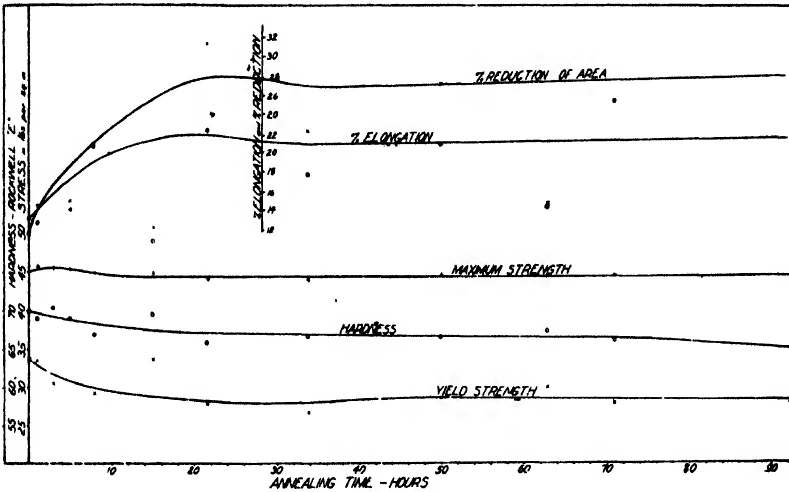

Fig. 15. Physical properties accompanying 650°F. anneal.

TABLE VIII (650° F. Anneal)

No.	Time Hrs.	Initial Hardness	Final Hardness	% Elong.	% Red	% Unif. Red.	% Unif. Elong.	.1% Yield Str.	.2% Yield Str.	Johnson's Yield	.7% Yield	.75% Yield	.8% Yield	Max. Stress	Breaking Stress	Stress on Final Area	Stress on Unif Area at Max. Load
103	1	68.9	77.2	13.0	14.7	9.21	17.5	32000	33250	29750	32250	32800	33350	45600	45600	52100	49500
104	3	70.1	78.6	10.5	11.7	7.09	13.7	29300	30250	27000	29000	29500	29750	45200	44800	50700	48600
105	5	68.9	79.1	14.5	15.3	11.85	18.0	32000	32750	29750	31750	32200	32600	45000	44700	52800	50900
106	8	66.7	81.0	21.0	21.1	15.45	18.2	28250	29000	25750	28350	28700	28900	44600	41500	53000	53100
107	15	69.3	78.0	11.0	12.4	4.74	30.0	32750	33400	30750	32600	33000	33300	44600	44400	50600	46900
100	21-3/4	65.4	78.0	22.5	31.9	12.70	44.0	26200	27500	23000	27400	27850	28250	43800	39800	57200	50000
108	34	66.5	79.8	16.0	22.5	12.70	25.8	25750	26600	23250	25600	26200	26500	43800	41600	53700	50300
102	50	66.2	80.2	21.0	27.3	14.8	39.0	27250	28350	24500	27750	28200	28500	44300	41300	57000	52000
109	63	64.1	78.5	14.5	14.8	10.7	17.0	29100	29750	26500	29100	29400	29650	44450	43200	50500	49500
110	71	65.9	80.0	25.5	35.8	15.9	56.0	26500	27490	23750	26700	27100	27500	44400	41100	64000	52800
112	94	63.7	78.2	21.5	29.2	12.1	42.0	26250	28000	23250	27500	28000	28500	43800	42100	59400	50200
113	119	63.3	76.8	22.5	33.3	16.8	43.0	26000	28200	21500	28250	28500	28750	43800	41500	59700	51600
111	143	63.0	77.8	21.0	21.7	13.7	36.5	24750	25750	21250	25800	26000	26150	43400	41500	56600	50300

values of these quantities are higher than for any of those of the previous treatments although the points deviate from the average curve much more. For this case the yield strength is 66.0% of the maximum stress with a mean deviation of 3.6%. For the 600°F. treatment these figures are 72.0% with a mean deviation of 1.13%.

Fig. 16 and Table IX give the values for the 600°F. heat treatment and show this temperature to be just on the border line between solution treatment and aging. There is a very slight increase in hardness which would indicate some additional precipitation and possibly

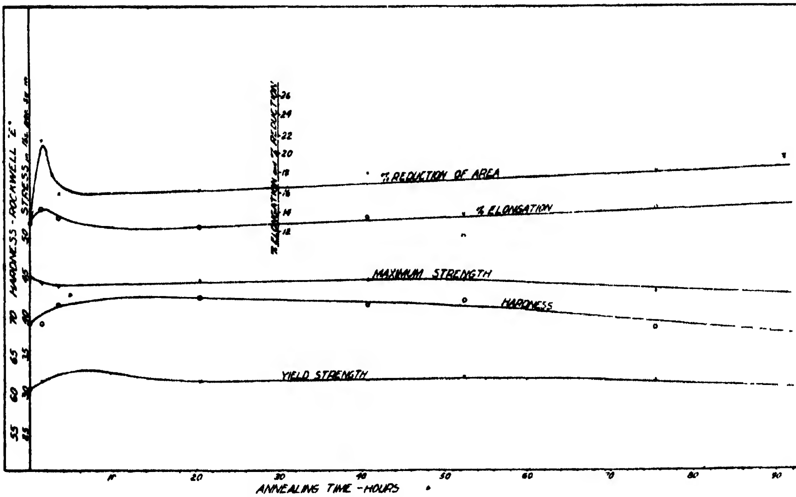

Fig. 16. Physical properties accompanying 600°F. anneal.

TABLE IX (600° F. Anneal)

No.	Time Hrs.	Initial Hardness	Final Hardness	% Elong.	% Red.	% Unif. Red.	% Unif. Elong.	.1% Yield Str.	2% Yield Str.	Johnson's Yield	.7% Yield	.75% Yield	.8% Yield	Max Stress	Breaking Stress	Stress on Final Area	Stress on Unif Area at Max. Load
9	1$\frac{1}{8}$	69.0	80.0	15.0	22.1	10.8	28.5	30500	31750	28250	31000	31600	32000	44200	42000	53900	49400
10	3-1/3	71.4	81 0	14 0	16.5	7.24	19.5	31750	32750	29500	31350	32000	32500	43900	43100	51500	48450
17	20$\frac{1}{8}$	72.2	78.0	13.0	16.7	10.6	20.5	30250	31500	27000	30750	31250	31750	44300	43400	52000	49600
23	40 3/4	71.3	79.5	14.0	18.6	11.3	20.0	30500	31500	27500	31000	31350	31600	44600	43600	53600	50300
44	52$\frac{3}{4}$	71.8	80.2	12.0	14.3	11.25	17.0	32500	32000	28250	32000	32600	33000	44450	44200	51500	50000
18	75$\frac{3}{4}$	68.2	74.8	15.0	18.8	12.8	23.3	30000	31500	26250	31000	31500	31900	42900	42100	51800	49100
20	95$\frac{1}{4}$	67.5	75.7	15.5	19.7	10.88	24.5	28500	30600	27250	28750	29000	29400	42400	41200	51200	47600
48	122	69.8	76.5	11.0	12.6	8.73	14.5	31000	31650	28750	31100	31500	31750	43600	43600	50500	48200
24	145	71.4	78.0	14.0	13.1	9.14	11.5	29750	30500	26750	30500	30750	31200	42700	42100	48300	47200
49	168	72.6	79.5	11.5	19.4	8.4	24.0	30000	31000	28750	30500	30850	31250	42500	42400	52600	48400
56	190	71 6	78.6	14.0	19.3	9.74	24.0	29000	30000	27000	29000	30000	30500	43400	41400	51200	48200
27	191 3/4	71.0	79.5	12.5	13.3	9.82	16	28750	30000	26500	29500	30000	30250	42700	42400	49200	47300

some over-aging with the long time anneal. Aside from the initial increase in ductility associated with relief of some of the strain hardening associated with the extrusion process, the per cent reduction in area and per cent elongation remain practically constant The microstructure for this treatment showed practically no change with the time of anealing.

The difference between the 650°F. anneal and the 600°F. anneal is further illustrated by the types of fractures obtained. The fractures of specimens heated at 600°F. varied very little with time of heating and are represented in Fig. 17. The 650°F. treatment shows a shear frac-

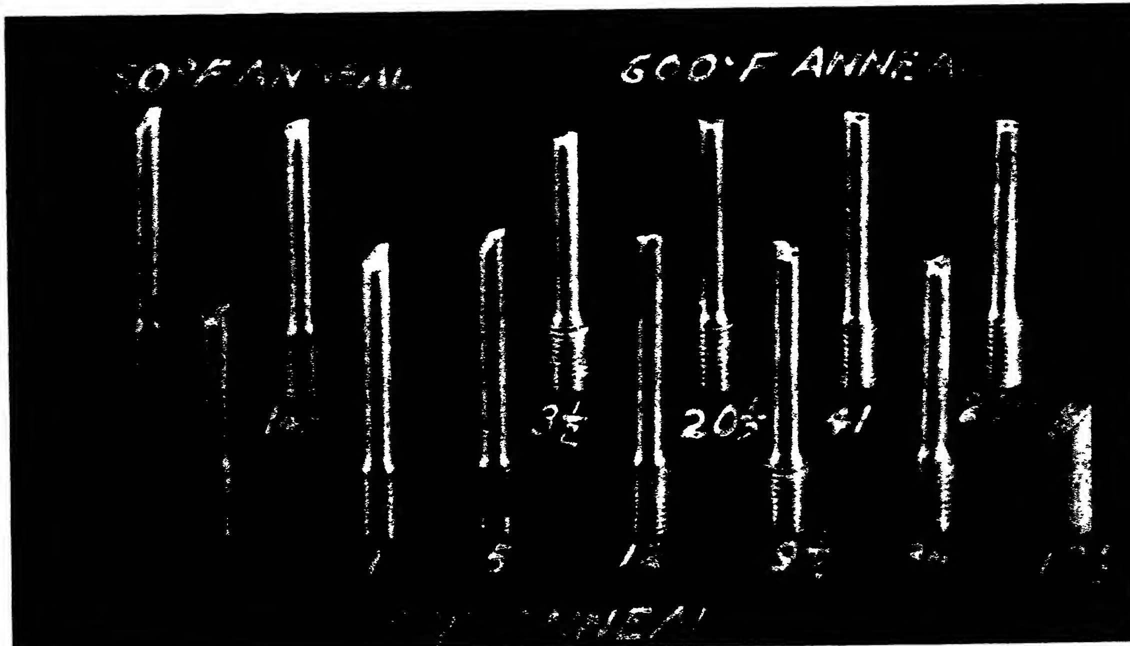

Fig. 17. Fracture pictures for 800°F., 650°F., and 600°F. annealing The numbers refer to hours at annealing temperature.

ture which is to be associated with a solution anneal as the Mg_3Al_2 particles which offer resistance on the potential planes of slip are dissolved. This difference is also evident in the difference between the percentage reduction of the final area, and also of the uniformly reduced area. The average of a group of specimens that were given the same time of heating at the respective annealing temperatures shows the 650°F. specimens to have a 25.7% reduction on the basis of the final diameter and 12.8% reduction on the basis of the uniformly reduced diameter. The corresponding figures for the 600°F. treatment are 16.6% and 10.2%.

Relation Between Characteristic Strength and Yield Values

Using the maximum strength as unity, the following table gives for the various annealing temperatures the yield strength and failing stresses expressed as a percentage of the maximum strength.

TABLE X

	.10% Str.	.20% Str.	Johnson's Limit	.70%	.75%	.80%	Maximum Strength	Break Strength	True Break Stress	True Stress at Maximum Load
825°F.	61.0	67.2	51.4	61.5	62.6	63.4	100.	96.7	125.2	115.5
800°F.	60.8	63.7	53.6	62.8	63.8	65.2	100.	96.3	129 6	115.3
775°F.	67.5	70.4	62.4	70.3	71.5	73.3	100.	97.2	121 0	114.0
725°F.	68.8	71.7	62.1	69.0	70.6	71.3	100.	96.0	121.0	112.0
675°F.	71.6	72.3	63.9	71.8	72.7	74.1	100.	96.4	125.5	113.0
650°F.	63.4	66.0	57.7	64.5	65.5	66.3	100.	95.9	124.2	113.6
600°F.	69.4	72.0	63.5	70.14	71.3	72.2	100.	98.0	118.6	112.0

The above table shows a definite relation between the maximum strength which is based on the original area and the true stress at maximum load. The true breaking stress and the breaking strength on the basis of the original area also bear a definite relation which may be of value in trying to explain failure due to combined stresses on the basis of simple tension stresses. A comparison of the last two columns shows that after the specimen ceases to reduce uniformly

along its length and necking starts that the additional cold work associated with the localized flow increases the average true stress approximately 10%. For the experiments conducted, this maximum average true stress has ranged from 45,000 lbs./sq." to 60,000 lbs./sq."

ACKNOWLEDGEMENTS

The writer wishes to express his indebtedness to Dean H. V. Carpenter for his encouragement in this study of the physical properties of magnesium alloys and to Dr. John A. Gann of the Dow Chemical Company for furnishing the material used. The writer is also indebted to Mr. Arthur Baker and Mr. Ivan Shirk for their assistance in the actual test work.

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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

« « « PULLMAN, WASHINGTON » » »

Vol 20 April, 1938 No 11

CHECK LIST OF WEIR FORMULAS

For Rectangular Sharp-Crested Weirs Without End Contractions

With Experimental Verification for Heads up to 0.5 ft.

By James G. Woodburn, Ph.D.

Recently Associate Professor of Hydraulic Engineering

State College of Washington

ENGINEERING BULLETIN No. 53

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

PUBLISHED BY THE STATE COLLEGE OF WASHINGTON

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Washington, under Act of August 24, 1912.

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

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Fig. 1 Test Weir and Flume

CHECK LIST OF WEIR FORMULAS

For Rectangular Sharp-Crested Weirs Without End Contractions

With Experimental Verification for Heads Up to 0.5 ft.

By James G. Woodburn

This bulletin is an outgrowth of the need the writer has experienced in teaching college classes for a more complete statement of weir formulas than is given in any textbook on hydraulics The fundamental theory of weir discharge is usually covered satisfactorily but the international multiplicity of formulas and experiments is largely omitted and statement is made of only one or two formulas which are favored by the author of the book The student is too often led to believe that the stated formula applies with equal accuracy to all sizes of weirs throughout the entire range of heads That this conclusion may be wide of the truth, especially with certain formulas which have been presented as authentic so often as to have become almost classical, is borne out by many previous experiments, as well as by the experiments reported in this bulletin on a weir in a glass-sided flume 1 ft wide for heads up to 0 5 ft

The bulletin presents, with brief statement of theory, 11 formulas for flow of water over rectangular sharp-crested weirs without end contractions Statement is made of the basis of each formula, whether derived from tests conducted by its proponent, or from study and analysis of other experimenters' data and formulas. If the formula is based directly on tests, data are given regarding the number of tests, height and length of test weir, range of test heads, and method of measurement of flow, so far as the writer has been able to gather such data from the publications available.

The original test data presented in this bulletin have been obtained over a period of six years in the Hydraulic Laboratory of the State College of Washington. Most of the tests were made by classes in experimental hydraulics under the supervision of the writer Some were made by the writer with laboratory assistants

SUMMARY OF TEST RESULTS

The data of 111 tests are presented in graphical form to show the accuracy of each of the formulas given in the check list, for this weir 0.823 ft. high in a glass flume 1 ft. wide with heads up to 0 5 ft. A picture of the weir and flume is shown in Figure 1. The tests indicate:

(1) Two formulas in the list—Harris, and Rehbock-1912—are outstanding in accuracy, particularly for heads from 0 10 to 0.50 ft. In 102 tests in this range, the average correction to be applied to results computed by the Harris formula to give the measured flow was 0.09 per cent, and for the Rehbock 1912 formula 0.05 per cent The Rehbock 1929 formula appears to be only slightly less accurate

(2) The Cline, and Fteley and Stearns formulas are not quite as close to the line of zero correction but for heads from 0 10 to 0 50 ft have an average accuracy within ½ of 1 per cent.

(3) The older "classical" formulas, for instance Francis and Bazin, are not in the same class of accuracy as the above five formulas, for weirs of this size with this range of heads. The Bazin formula is shown to over-read more than 20 per cent at heads of 0 05 ft and over 4 per cent at heads of 0.50 ft. The Francis formula on the other hand under-reads more than 5 per cent at heads around 0.05 ft. and about 2 per cent with heads from 0.20 to 0 50 ft Other formulas based on Francis or Bazin are likewise in error.

(4) For the low heads of 0.05 to 0.10 ft the Rehbock, Harris and Cline formulas appear to give results within 1 per cent of the measured flow. There are, however, not enough test results in this range to be conclusive in view of the relatively large per cent of error in computed results caused by small error in measurement of head

It is pleasing to note that the two formulas shown to be most accurate are the easiest of all 11 to apply to the computation of weir flow

Some years ago following international discussion of the weir method of measuring flowing water many engineers came to the conclusion that so many variables entered into the computation of flow over a sharp-crested weir that other devices offered more promise for accurate flow measurement.

The close agreement of the tests reported in this bulletin with at least two available formulas as well as the ease with which a weir and flume of this type can be designed and built indicate that this distrust is not well-founded and strengthen the writer's confidence that the sharp-crested rectangular weir without end contractions is the most accurate device yet discovered for the continuous measurement of flowing water.

STATEMENT OF FORMULAS

The 11 formulas are stated below in order of date of publication The nationality of the investigator is given in each case

The notation used is

Q = discharge in cu. ft. per sec.

H = head on the weir in ft.

L = length of weir in ft = width of flume

P = height of weir in ft.

$D = H + P$ = depth of water in flume in ft.

v = velocity of approach in ft. per sec

g = 32 16 ft. per sec. per sec., therefore

$$\sqrt{2g} = 8\,020$$

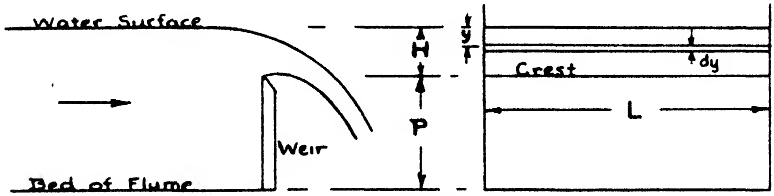

Fig 2. Side and Front Elevations of Rectangular Weir Without End Contractions.

Francis (U.S., 1852):

$$Q = 3.33L\left[\left(H+\frac{v^2}{2g}\right)^{\frac{3}{2}} - \left(\frac{v^2}{2g}\right)^{\frac{3}{2}}\right]$$

Fteley and Stearns (U S, 1883):

$$Q = 3.31L\left(H + \alpha\frac{v^2}{2g}\right)^{\frac{3}{2}} + 0.007L$$

The authors give tables for α, recommending in general for suppressed weirs a value of 1.5.

Bazin (France, 1888):

$$Q = \left(3.248 + \frac{0.0789}{H}\right)\left(1 + 0.55\frac{H^2}{D^2}\right) L H^{\frac{3}{2}}$$

Frese (Germany, 1890):

$$Q = \left(3.288 + \frac{0.0368}{H}\right)\left(1 + 0.56\frac{H^2}{D^2}\right) L H^{\frac{3}{2}}$$

Rehbock (Germany, 1912):

$$Q = \left(3.235 + \frac{0.0167}{H - 0.0094} + 0.428\frac{H}{P}\right) L H^{\frac{3}{2}}$$

Barnes (England, 1916):

$$Q = 3.324 L^{0.98}\left(H + 1.29\frac{v^2}{2g}\right)^{1.49}\left(L + 2H\right)^{0.02}$$

King (U S, 1918):

$$Q = 3.34\left(1 + 0.56\frac{H^2}{D^2}\right) L H^{1.47}$$

Swiss (Switzerland, 1924):

$$Q = \left(3.288 + \frac{0.0108}{H + 0.0052}\right)\left(1 + 0.5\frac{H^2}{D^2}\right) L H^{\frac{3}{2}}$$

For mention of Schoder and Turner formula (U S, 1929) see page 17.

Rehbock (Germany, 1929):

$$Q = \left(3.228 + 0.435\frac{H_e}{P}\right) L H_e^{\frac{3}{2}}$$

where the "substitute head" $H_e = H + 0.0036 ft.$

Cline (Canada, 1935):

$$Q = 3.276 L \left(1.0195\right)^{H} H^{f} \times 10^{KH}$$

$$\text{where} \quad f = 1.5064 H^{0.0081} \quad \text{and} \quad K = \frac{0.2713}{1 + 6.1452 P^{\frac{3}{2}}}$$

In logarithmic form:

$$\log \frac{Q}{L} = 0.5154 + 0.0084\,H + 1.5064\,H^{0.0081} \log H + KH$$

Harris (U.S., 1936):

$$Q = \left(3.27 + \frac{C}{H} + 1.5\frac{H^2}{D^2}\right) L H^{\frac{3}{2}}$$

where C varies with water temperature from 0.023 at 39°F. to 0.018 at 68°F.

FUNDAMENTAL THEORY

Development of the basic formulas for weir discharge dates back into the early history of hydraulic theory and can be repeated here briefly.

Referring to Fig. 2, the discharge through the elementary strip of area L·dy under head y is

$$dQ = L\,dy\sqrt{2gy} \tag{1}$$

The total theoretical discharge is then

$$Q = \int_0^H L\sqrt{2g}\,\sqrt{y}\;dy = \frac{2}{3}\sqrt{2g}\,L H^{\frac{3}{2}} \tag{2}$$

Application of a coefficient of discharge of 0.62 gives the approximate base formula

$$Q = 3.3\,L H^{\frac{3}{2}} \tag{3}$$

A more precise fundamental formula is obtained by including both velocity head and static head on the elementary strip. Equation (1) then becomes

$$dQ = L\,dy\sqrt{2g\left(y + \frac{V^2}{2g}\right)} \tag{4}$$

from which

$$Q = \int_0^H L\sqrt{2g}\sqrt{y + \frac{V^2}{2g}}\;dy = L\sqrt{2g}\left[\frac{2}{3}\left(y + \frac{V^2}{2g}\right)^{\frac{3}{2}}\right]_0^H$$

$$Q = \frac{2}{3}\sqrt{2g}\,L\left[\left(H + \frac{V^2}{2g}\right)^{\frac{3}{2}} - \left(\frac{V^2}{2g}\right)^{\frac{3}{2}}\right] \tag{5}$$

With a discharge coefficient of 0.623, this equation becomes the well-known Francis formula with velocity of approach correction:

$$Q = 3.33L\left[\left(H+\frac{v^2}{2g}\right)^{\frac{3}{2}} - \left(\frac{v^2}{2g}\right)^{\frac{3}{2}}\right] \tag{6}$$

Fteley and Stearns and Barnes use modified forms of the Francis formula.

The form of velocity of approach correction used by Bazin, Frese, King, and the Swiss Society of Engineers and Architects can be derived by algebraic transformation of Equation 6.

Letting

$$\frac{v^2}{2g} = h_v , \tag{7}$$

$$Q = CLH^{\frac{3}{2}}\left[\left(1+\frac{h_v}{H}\right)^{\frac{3}{2}} - \left(\frac{h_v}{H}\right)^{\frac{3}{2}}\right]$$

By expansion the quantity in brackets becomes

$$\left[1+\frac{3}{2}\,\frac{h_v}{H}+\frac{3}{8}\left(\frac{h_v}{H}\right)^{\frac{3}{2}} - - - - - - \left(\frac{h_v}{H}\right)^{\frac{3}{2}}\right] \tag{8}$$

Dropping all terms except the first two and substituting for h_v its approximate value

$$h_v = \frac{v^2}{2g} = \frac{Q^2}{A^2 \cdot 2g} = \frac{\left(CLH^{\frac{3}{2}}\right)^2}{(LD)^2 \cdot 2g} = \frac{C^2}{2g}\cdot H \cdot \frac{H^2}{D^2} , \tag{9}$$

the equation for discharge becomes

$$Q = CLH^{\frac{3}{2}}\left[1 + C_1\frac{H^2}{D^2}\right] \tag{10}$$

where

$$C_1 = \frac{3}{2}\cdot\frac{C^2}{2g}$$

If $C = 3.3$, $C_1 = 0.25$. Test results, however, lead to empirical values of C_1 from 0.50 to 0.56, with C modified to decrease slightly as H increases, with a minimum value of about 3.3 King uses a constant value of C of 3.34 with a modified exponent of H.

Rehbock and Harris correct for velocity of approach by means of an additive term instead of a factor, resulting in greater simplicity of application. Harris also causes the value of C to vary with the water temperature, being the only one of the ten formula writers to do so.

The effect of a change in temperature from 39 degrees F to 53½ degrees on the accuracy of the Harris formula is shown in Fig. 3.

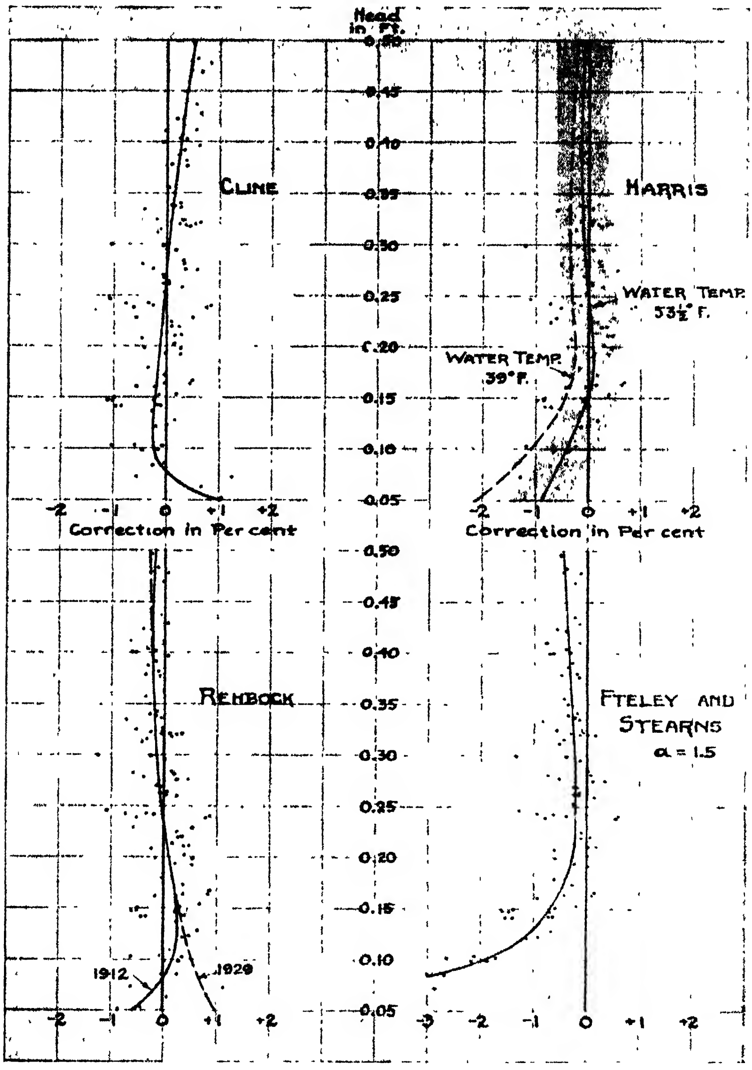

Fig. 3. Accuracy of Weir Formulas. Correction to be applied to flow computed by formula to give measured flow of the test. Solid lines are drawn to fit the 111 test points shown. Dashed lines show effect of variations in formulas. Edges of band on Harris diagram are ½ per cent each way from curve

GENERAL DESIGN REQUIREMENTS FOR STANDARD WEIR

Out of 100 years of experiment and thought on sharp-crested weirs have come certain fundamental principles of design which are generally agreed upon These principles, as they apply to weirs without end contractions, are:

1. The upstream face of the weir plate shall be vertical and smooth.
2. The crest edge shall be level, shall have a square upstream corner, and shall be so narrow that the water will not touch it again after passing the upstream corner.
3. The sides of the flume shall be vertical and smooth and shall extend a short distance downstream past the weir crest
4. The nappe shall be thoroughly aerated.
5. The approach channel shall be of uniform cross-section for a sufficient distance above the weir, or shall be so provided with baffles, that a normal distribution of velocities shall exist in the flow approaching the weir, and the water surface shall be free of waves or surges
6. The head shall be measured at a sufficient distance upstream from the weir to avoid the surface curvature

The proponents of the various formulas have in general agreed on most of these fundamentals of design They have in some cases limited the application of their formulas or modified the general specifications Such exceptions are noted below under discussion of the individual formulas.

Further studies are needed to determine the tolerance which may be granted in each of the above six items of design without affecting measurably the discharge of a standard weir Test data and discussions regarding effect of roughness and rounding of crest, of roughness of weir plate, and of irregular velocities in the approach channel are given in the paper, "Precise Weir Measurements," by Schoder and Turner, with subsequent discussion, in Transactions, American Society of Civil Engineers, 1929 This paper is the most important international symposium on weir measurement of flowing water which has yet appeared. Water Supply Paper No 200 of the U. S Geological Survey, entitled "Weir Experiments, Coefficients and Formulas," by R. E. Horton, (1902), gives information on early weir experiments.

Discussions of effects of variation in weir design may also be found in standard works on hydraulics and in references given therein

It appears that particular study needs to be given to the amount of aeration required under the nappe, in order to determine, for the case of a weir plate in a flume which continues on for some distance past the weir, whether or not sufficient air can be introduced under the nappe through holes in the sides of the flume or by pipes through the nappe itself to equal the aeration obtained when the nappe falls free in air, as at the end of a flume. Inability to properly aerate the nappe of a weir in a continuing flume would detract from the usefulness of a standard weir under field conditions, since head is usually at too much of a premium to permit of providing a free fall for the nappe

BASIS OF DERIVATION OF FORMULAS

Seven of the 11 formulas are based entirely or partly on original tests by the proponent of the formula The other four were derived from tests and formulas of other experimenters The source of each formula and, in case of original tests, brief data in regard to size of weir, range of test heads, and method of measurement of flow are given in the following pages Further details may be obtained by consulting the original publication, reference to which is given in each case

FRANCIS

Reference: Lowell Hydraulic Experiments, D Van Nostrand & Co, 4th Edition, 1883

Basis: Experiments in 1852 at canal locks at Lowell, Mass Most of Francis' experiments were on weirs with end contractions The record shows only 17 experiments on a weir with width of approach channel the same as the length of the weir Moreover, in only 5 of these tests was there an extension of the sides of the flume past the weir

The length of weir in these 17 tests was 9 995 ft, the height of weir was 5 048 ft, and the range of test heads was from 0 7362 to 1 006 ft.

The head was measured with two hook gages reading in wooden stilling wells, one on each side of the flume and connected by pipes to the bottom of the flume 6 ft upstream from the weir Because of fluctuations in water surface elevation during tests, amounting to as much as 0 03 ft., a mathematical mean was determined for the readings of each gage and the average of the two results was used for the head.

The flow was measured in a timber flume 102 ft. long and 11.6 ft wide. A swinging gate diverted flow into and out of the measuring

basin. Time was measured by means of an electrical sounder and a marine chronometer. Correction was made for leakage.

FTELEY AND STEARNS

Reference: Transactions American Society of Civil Engineers, 1883.

Basis: Original experiments in 1877-78 in Sudbury Conduit near Boston: Tests on weirs without end contractions included:

(a) 31 experiments on a weir 5 ft. long, 3.17 ft. high, with a range of head from 0.0735 to 0.8198 ft., and a range of flow from 0.3652 to 12.75 cfs. The water temperature was about 36 deg. F

(b) 10 experiments on a weir 19 ft long, 6 55 ft. high, with a range of head from 0.47 to 1.60 ft., and a range of flow from 20 to 130 cfs The water temperature varied from 34 to 45 deg. F.

The head in these tests was measured 6 0 ft upstream from the weir. The flow was measured volumetrically in conduits, the volume of which was determined by cross-section measurements. The total measuring capacity was about 300,000 cu. ft.

(c) To determine values of the velocity-head coefficient 94 experiments were made on weirs 5 ft. long with heights of 0.50 ft., 1 00 ft., 1.70 ft., 2.60 ft., and 3.56 ft., and with a range of heads from 0 1884 to 0.9443 ft. The water temperature was about 40 deg F.

Fteley and Stearns state that their formula does not apply to heads less than 0.07 ft

BAZIN

Reference: Annales des Pont et Chausees, 1888. (Translation by Marichal and Trautwine, Proceedings Engineers Club of Philadelphia, 1890.)

Basis: Original experiments, begun in 1886, in a canal at Dijon, France.

(a) 153 tests in which the flow was measured volumetrically;

Series	No. of tests	Length of weir Ft.	Height of weir Ft.	Range of heads Ft	Mean water temperature Deg. F.
1	67	6.56	3.72	0 194 to 1.012	59
2	38	3.28	3.72	0.188 to 1.34	57
3	48	1.64	3.30	0.191 to 1.78	49

The head was measured in stilling wells, one on each side of the channel 16.40 ft. upstream from the weir. The flow was measured volumetrically in a channel 656 ft. long, 6.56 ft. wide, with side walls 4 ft. high. A drop-gate on the weir crest was opened and closed to start and stop each test. Before opening this gate the upstream channel was filled through headgates to the approximate test head desired.

During the test the headgates were manipulated to maintain a nearly constant flow. Correction was made for leakage

(b) 228 tests of weirs of various heights in series with a "standard" weir 3.72 ft. high, to determine the effect of velocity of approach. All the weirs were 6.28 ft. long. The heights of the experimental weirs were 2.47 ft., 1.65 ft., 1.16 ft., 1.14 ft., and 0.79 ft. The range of heads on the standard weir was from 0 297 ft. to 1.48 ft. The range of water temperature was from 41 deg. F to 68 deg., with most of the tests at temperatures of 50 to 64 deg. F. The flow in these tests was not measured volumetrically.

FRESE

Reference: Zeitschrift Verein Deutscher Ingenieure, December, 1890.

Basis: Study of tests and formulas by Castel, Lesbros, Francis, Fteley and Stearns, and Bazin. Frese made an extended series of measurements on weirs with end contractions, using rectangular notches of various lengths in the top of a sliding timber gate in a canal lock. Because of the framework at the sides of the canal, on which the gate was operated, no tests of full-width weirs were possible

REHBOCK

References: Handbuch der Ingenieurwissenschaften, 1912, III Teil (Wasserbau), II Band, pages 55-61.

Zeitschrift Verein Deutscher Ingenieure, 1929.

Basis: 1912 formula: Original tests covering a period of many years in the Karlsruhe laboratory.

Heights of test weirs: 0.39, 0 66, 0.82, and 1.64 ft Range of heads up to about 0.6 ft. Water temperature 64 to 68 deg. F., but no perceptible effect on coefficient was found when water was cooled down to 45 deg. F.

Out of 170 check tests made in the spring of 1912, only 15 showed a variation from the formula of more than ½ per cent, the average error, computed by the method of least squares, being 0.23 per cent

Rehbock states the formula is good for heads from about 0 03 ft up to 0.8 P, and for all heights of weir above 0.33 ft.

Rehbock revised the 1912 formula the following year by modifying slightly the second term in parentheses, giving it the value

$$\frac{.0175}{H}$$

The 1913 formula does not fit the tests reported in this bulletin quite as closely as does the 1912 formula.

1929 formula: To develop a "homogeneous" formula based on a wider range of tests than those at Karlsruhe, Rehbock studied the results of 280 tests made by other experimenters in recent years, including Schaffernak in Vienna, Lindquist in Stockholm, the Swiss Bureau of Water Resources at the Amsteg Powerhouse, and Schoder, Turner and Jones at Cornell University.

The range of weir heights in these tests was from 0 50 to 4 00 ft ; the range of heads was from 0 0335 to 2 71 ft.

BARNES

Reference: Hydraulic Flow Reviewed, E & F. N. Spon, Ltd , 1916

Basis: Study of experiments by Francis, Boileau, Fteley and Stearns, Bazin, University of Wisconsin, and Rafter at Cornell University. The experiments studied were made on weirs from 2 5 to 19 ft. long, with a range of heads up to 6 ft and with a range of flows from 0.75 to 319 cfs

Barnes states as special conditions for use of his formula.

The height of the weir should be at least 2H, with a minimum of 1 ft.

The tail water should not rise higher than 3 in below the crest

The head should be measured preferably at 6 ft upstream from the weir, but apparently not much error will result if it be measured between 6 and 16 ft upstream, provided the channel be smooth and the mean velocity not greater than 1 ft per sec

KING

Reference: Handbook of Hydraulics, McGraw-Hill Book Co , First Edition, 1918

Basis: Work and experiments of Francis, Fteley and Stearns and Bazin, with closer agreement with the formula of Bazin than of the other two Test data in support of this agreement were obtained by tests of a weir duplicating the dimensions of Bazin's standard weir 6.56 ft. wide, 3.72 ft high, with heads ranging from 0 4 to 4 0 ft The water was measured by chemical gaging

SWISS

(Society of Engineers and Architects)

Reference: Contribution a l'etude des Methodes de jaugeage, Bulletin No. 18, Swiss Bureau of Water Resources, Bern, 1926.

Basis: An extensive series of tests of methods of water measurement was made in 1922 in the tail race of the Amsteg powerhouse. The flow from a turbine was measured volumetrically, by current meters and by chemical gaging. The head on a weir was read and the flow was computed by the Rehbock 1912, Frese and Bazin formulas

and by the formula proposed by the Swiss Society, for comparison with the measured flow.

Volumetric measurements were made in 71 tests. The range of head on the weir was from 0.353 to 2.63 ft. The weir was 2.62 ft high with a crest length of 9.8 ft. The usable capacity of the measuring basin was 5650 cu ft. The tests indicated that the Rehbock and Swiss formulas were more accurate than the other two and were satisfactory for turbine flow measurements under the conditions of the tests.

SCHODER AND TURNER

Reference: Transactions American Society of Civil Engineers, 1929

Basis: Extensive original tests at Cornell University

The formula is:

$$Q = 3.33L\left[\left(H + \frac{V_a^2}{2g}\right)^{\frac{3}{2}} + 0.3H\frac{V_b^2}{2g}\right]$$

where V_a is the mean velocity in the channel of approach above crest level, V_b is the mean velocity in the channel of approach below crest level.

This formula requires supplementary velocity measurements in the channel of approach and may be a solution of the problem of accurate flow measurement if a standard weir cannot be developed. If however standards of construction can be developed under which a weir will measure flow accurately, velocity determinations are not only unnecessary but also could not be made without upsetting the standard conditions.

No velocity measurements were made in the tests described in this bulletin so the accuracy of the Schoder and Turner formula could not be determined.

CLINE

Reference: Transactions American Society of Civil Engineers, 1935

Basis: Mathematical study of results of 805 separate volumetric measurements selected from a total of 2438 such measurements made at Cornell University and reported by Schoder and Turner in Transactions A.S.C.E., 1929. The length of weir was 4.22 ft, the height varied from 0.5 to 7.5 ft, and the range of heads was from 0.012 to 2.75 ft. The head was measured 11.74 ft upstream from the weir. The flow was measured by diverting it into a calibrated circular standpipe 60 ft high, with a capacity of 1700 cu. ft.

HARRIS

Reference: Hydraulics, John Wiley & Sons, 1936.

Basis: Study of other formulas and experiments, supplemented by tests at the University of Washington on a weir 4 ft. high and 2 ft. long with heads up to 1 ft. The head was measured 4 ft. upstream from the weir. The flow was measured volumetrically in a tank previously calibrated by weighing.

Harris states in regard to the formula:

The term C/H is the correction for "frictional drag," or the resistance to vertical flow along the weir face, which affects the contraction of the nappe. This term is affected by the viscosity of the water.

The term 1.5 H^2/D^2 is the correction for "channel restriction" and is to account for velocity of approach and incomplete contraction

H should preferably be kept less than 0.4D

EXPERIMENTAL VERIFICATION

Comparison of each of these eleven formulas with the results of 111 tests in the hydraulics laboratory of the State College of Washington is shown in Figures 3 and 4 The accuracy of the formulas in closest agreement with the measured flows—Rehbock, Harris, Cline, and Fteley and Stearns—is shown in Fig. 3. The dots show for each test head the per cent correction which must be applied to the flow computed by the formula to give the measured flow of the test. Thus if the points show negative correction the formula gives results larger than the measured flow, and vice versa.

Fig. 4 shows the correction curves for the other six formulas The individual test points are not shown, and in fact only enough of them were computed to establish the curves, the relative location of the test points being similar for all formulas.

The weir on which these tests were made was a smooth vertical plate 0.823 ft. high in a glass-sided flume 1.000 ft. wide The crest was monel metal with right-angled upstream corner and flat top 1/32 in. wide. The head was measured with a hook gage reading in a 2-in. gage glass mounted on the outside of the weir flume in the plane of the weir and connected by glass tube, rubber tube, and iron pipe with three piezometer holes in the bottom of the flume 3.0 ft. upstream from the weir. The flow was measured volumetrically in a concrete

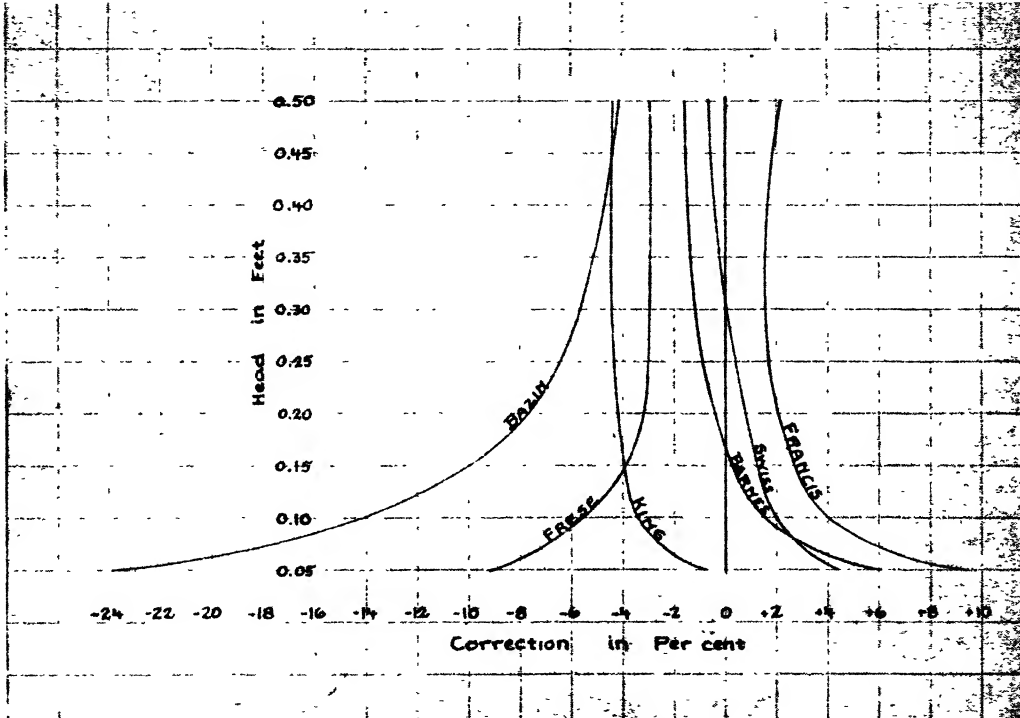

Fig. 4. Comparative accuracy of six weir formulas. Corrections to be applied to flow by indicated formula to give measured flow Curves based on 111 tests.

pit which had been calibrated gravimetrically, using 62.40 lb. per cu. ft. for the weight of water. Further details of test equipment are given below.

Laboratory Test Equipment

A centrifugal pump drew water from four interconnected pits with a combined water surface area of about 200 sq. ft The water was pumped to a standpipe 4 ft. in diameter equipped with an overflow pipe 25 ft. above the test weir, which wasted water back to the pump pit and thus limited fluctuation of water level in the standpipe to a few tenths of a foot.

From the side of the standpipe water flowed through a 4-in. pipe into a tank on the second floor of the laboratory 15 ft above the test weir A contracted weir in the side of this tank also wasted water to the pump pits and further reduced fluctuations in the test flow During all tests, waste flow was maintained from both standpipe and upstairs weir tank. As a result, the fluctuations of the test head were ordinarily not greater than 0 0002 ft from the average at the small and intermediate flows and not more than 0 0010 ft at the largest flows.

From the base of the upstairs weir tank, the test water flowed through a 5-inch pipe down into the entrance tank at the head end of the test-weir flume This tank, shown in Fig 5, was 2 ft square in plan, with its top level with the top of the flume and its bottom 5 ft below the bed plate of the flume The 5-inch pipe extended downward to within a foot of the bottom of the tank A gate valve in the pipe controlled the amount of the test flow The entrance from the tank to the test flume was curved on sides and bottom to give smooth transition flow. Short lengths of plank on the water surface in the tank eliminated surface waves.

Description of Test Weir and Flume

The necessity for rigidity was kept in mind in designing the steel framework of the flume Stresses and deflections were calculated and suitable members selected to keep these values within low limits. The use of welding equipment in the college shops eliminated the necessity for designing a riveted frame and facilitated both design and construction

The position of the brick piers was fixed within narrow limits by the supporting walls under the floor. The position of the flume on the

piers was determined by the amount of space for entrance and discharge tanks as well as by the desire to have minimum deflection of the flume at the weir.

Details of design of the flume are shown in Fig 5. The flume consisted of 5/8-in plate glass sides held by an angle iron frame which

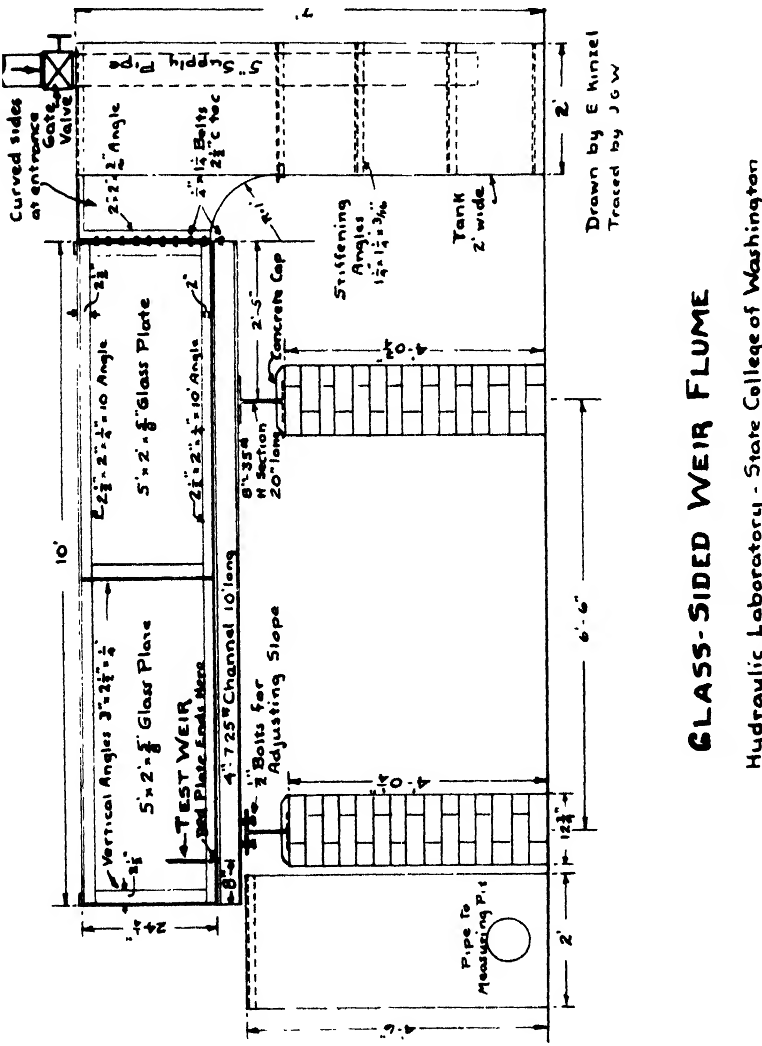

Fig 5 Side Elevation of Test Flume

was welded to the ½ in. steel bed plate. The bed plate rested on longitudinal 4-in. channels bearing on transverse H-beams which were embedded in concrete caps on the brick piers.

The four plate-glass sections, each 5 ft. long and 2 ft. high were set in shallow notches in the bed plate and held at the top by steel clips. Asphaltic roofing compound was used in all spaces between glass plates and steel frame and in the butt joints between the plates. This material has given excellent results, as it is stiff enough to prevent movement of the glass plates but does not harden sufficiently to put undue stress in the glass. The joints, moreover, have remained water tight throughout six years of use of the flume

Weir Plate

The test weir plate consisted of a monel-metal plate 3/16 in. thick and 4 in wide, spliced to a steel plate 3/16 in thick The splice plate was ¼-in. steel on the downstream side of the weir. Details of construction are shown in Fig 6 The monel-metal crest plate was attached to the splice plate with ⅛-in brass rivets while the steel joints were welded. Vertical stiffening strips of ¼-in steel were welded to the ends of the weir plate.

The crest edge was 1/32 in. wide, with upstream corner square and with downstream corner beveled The weir plate was held in position by bolting it to an angle welded to the bottom of the bed plate at its downstream end, which was 8 in short of the ends of the glass sides The nappe was therefore constrained on the sides for a distance of 8 in. past the crest.

The weir plate was cut 1/16 in. shorter than the 12-in width of flume. The ends of the plate were grooved and string packing laid in the grooves. The cracks were then shellacked to form water-tight end joints against the glass. The upper corners of the crest were finished out with permatex.

Measurement of Head

Three ¼-in. holes were drilled in the bed plate of the flume in a line 3.0 ft. upstream from the weir. The holes were threaded and ⅛-in. nipples were screwed in from below. The upper ends of these nipples were then filed flush with the bed of the flume.

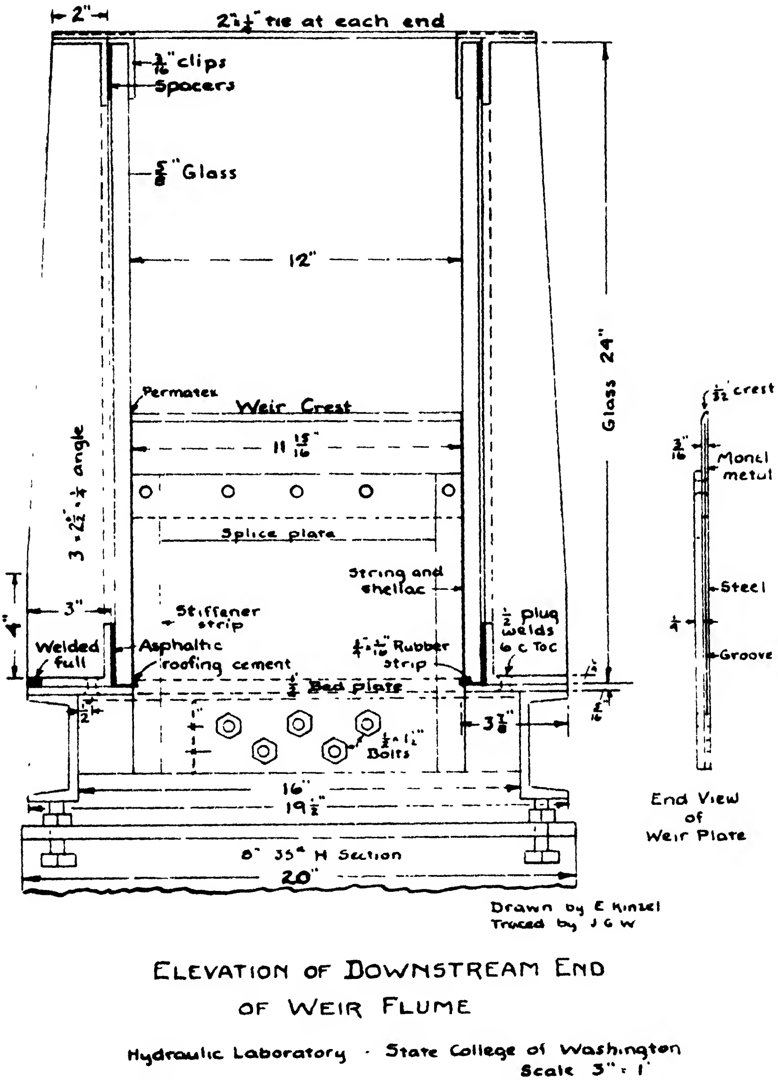

Fig. 6. Elevation of Test Flume at Downstream End

The bottom ends of the nipples were connected by a manifold of ⅛-in. pipe fittings. This manifold was connected by rubber and glass tubing through a rubber stopper into a 2-in. vertical gage glass at-

tached to the outside of the weir flume in the plane of the weir. A Gurley standard hook-gage was mounted to the flume by means of an angle iron The hook of the gage was bent in so that it would enter the gage glass and so that the point of the hook would be at least ½ in away from the glass to avoid effect of curvature of the meniscus

In all observations of head the hook-gage was read to the nearest 0.0001 ft Technique in the later tests called for draining the gage glass and rubber tube between each two runs to avoid error due to temperature changes of the water in the tube.

Zero Reading

Determination of the reading of the hook-gage with zero head on the weir was made with great care before and after each series of tests An auxiliary hook gage and a small level tube were used in the determination.

The auxiliary hook gage was supported by an angle iron frame laid across the top of the weir flume With the point of this gage about ½ in upstream from the crest, the level tube was balanced on the crest with one end resting very lightly on the point of the gage, and the bubble centered. The level tube was then reversed and the bubble brought halfway back to center The auxiliary gage was then read.

With water standing in the flume at about crest level, both hook gages were carefully set simultaneously with points at the water surface in flume and gage glass respectively The difference in the two auxiliary gage readings, applied to the reading of the main gage with point at water surface, gave the reading of the main gage with point at crest level

Measurement of Flow

Water flowing over the test weir dropped into a tank from which a pipe led to the measuring pit. In the earlier tests a 6-in. cast iron pipe was used with a goose-neck arrangement at the discharge end which could be swung on the pipe threads to divert the flow across a partition into the measuring pit at the beginning of the test run and back to a waste pit at the end For the later tests a 9-in galvanized pipe was installed with fixed end discharging downwards directly over

the partition. A sheet-iron flipper was designed which was pivoted in the concrete partition and by means of which the flow was more easily diverted from one pit to the other. Time of all tests was measured with a Meylan 1/10-sec. stop watch

The water surface elevations in the measuring pit at the beginning and end of each test run were determined in nearly all the tests by means of a hook-gage reading in a 2-in gage glass connected to the pit by a piezometer tube The area of the pit, throughout the 2-ft vertical range of the hook-gage was calibrated twice in the last seven years by the use of weighing scales on the second floor of the laboratory. The volumetric measuring capacity with this hook-gage was about 125 cu. ft

In order to obtain a greater length of run than possible with the hook-gage, tests made in 1937 at heads greater than 0.3 ft had the flow measured by means of a wooden staff-gage which had been previously calibrated to read directly in cu ft content of the measuring pit The staff-gage was mounted parallel with a 1-in vertical glass tube which was connected by piezometer tube with the pit The staff-gage was read to 0.1 cu ft and a total volume of from 300 to 400 cu ft was accumulated during each test run.

TABLE I

Accuracy of Four Weir Formulas In Different Ranges of Head

Average Correction to Be Applied to Flow Computed by Formula to Give Measured Flow

Range of Head Ft	No of Tests	Average Per Cent of Correction			
		Harris	Rehbock 1912	Fteley & Stearns	Cline
0.05 to 0.10	9	—0.64	—0.03	—4.01	+0.26
0.10 to 0.20	28	—0.17	+0.15	—0.84	—0.28
0.20 to 0.30	33	—0.01	—0.03	—0.24	—0.04
0.30 to 0.40	24	—0.06	—0.16	—0.24	+0.20
0.40 to 0.50	17	—0.13	—0.24	—0.41	+0.37
0.10 to 0.50	102	—0.09	—0.05		

Discussion of Results

The graphical presentation in Figs. 3 and 4 of the results of the 111 tests has been referred to on page 18 Table I shows for four

formulas the average per cent correction in different ranges of head between 0.05 and 0.50 ft.

The general consistency of the test results is indicated by the fact that 92 of the 111 points fall within the ½ per cent band shown on the Harris diagram in Fig 3. In this diagram the points are computed with a value of C of 0.0205 corresponding to a water temperature of 53½ degrees F, which was about the average water temperature of the tests. The solid line represents the average correction for these points, while the dashed line represents the average correction for a value of C of 0.023, corresponding to a water temperature of 39 degrees F

In the Rehbock diagram in Fig. 3, the points and solid line represent results computed by the 1912 formula, while the dashed line shows the correction for the 1929 formula.

The 111 heads tested, with respective measured flows, flows computed by each of the four most accurate formulas, and corresponding per cent of error are shown in Table II. The number of each test run indicates the year of the test and its number in that year Thus Run Number 19-7 was test number 19 in 1937.

The number of tests in each year with the average zero head readings of the main hook-gage are shown below

Year		Number of Tests	Zero Head Reading
1931	Spring	28	1.2393
1932	Spring	18	1.5036
1933	Spring	6	1.5041
1933	Fall	4	1.5044
1934	Spring	6	1.5044
1935	Spring	4	1.5044
1935	Fall	15	1.5035
1937	Spring	24	1.5038
1937	Spring	6	1.5036
	Total	111	

The height of the test weir in 1931 was 0.836 ft.; in all runs after that year it was 0.823 ft.

Run No.	Head	Measured Flow	Harris Computed Flow	Harris Correction	Rehboch 1912 Computed Flow	Rehboch 1912 Correction	Fteley and Stearns Computed Flow	Fteley and Stearns Correction	Cline Computed Flow	Cline Correction
	Ft	Cfs.	Cfs.	%	Cfs.	%	Cfs.	%	Cfs.	%
19-5	.0810	.04183	.04236	-1.20	.04220	-0.88	.04520	-7.45	.04147	+0.87
1-3	.0526	.04382	.04420	-0.86	.04401	-0.43	.04702	-6.81	.04336	+1.06
2-1	.0624	.05588	.05621	-0.59	.05584	+0.07	.05870	-4.81	.05550	+0.68
13-7	.0717	.06873	.06846	+0.39	.06797	+1.12	.07075	-2.86	.06789	+1.24
5-5	.0730	.06928	.07022	-1.30	.06972	-0.63	.07247	-4.40	.06968	-0.57
21-1	.0845	.08599	.08661	-0.72	.08601	-0.02	.08862	-2.97	.08622	-0.27
20-1	.0854	.08751	.08789	-0.43	.08728	+0.26	.08992	-2.68	.08754	-0.03
2-2	.0787	.1077	.1084	-0.65	.1077	0	.1101	-2.18	.1082	-0.46
2-3	.0987	.1080	.1084	-0.37	.1077	+0.28	.1102	-1.91	.1082	-0.18
3-1	.1027	.1145	.1148	-0.26	.1141	+0.35	.1165	-1.72	.1146	-0.09
4-1	.1027	.1134	.1148	-1.22	.1141	-0.61	.1165	-2.66	.1146	-1.05
10-5	.1040	.1161	.1169	-0.68	.1162	-0.09	.1186	-2.11	.1168	-0.60
19-1	.1218	.1470	.1472	-0.14	.1465	+0.34	.1487	-1.14	.1473	-0.20
14-7	.1230	.1494	.1494	0	.1487	+0.47	.1508	-0.93	.1494	0
4-2	.1284	.1594	.1591	+0.19	.1584	+0.63	.1605	-0.69	.1592	+0.13
1-5	.1366	.1739	.1742	-0.17	.1735	+0.23	.1755	-0.91	.1744	-0.29
22-1	.1415	.1821	.1834	-0.71	.1827	-0.33	.1847	-1.41	.1837	-0.87
23-1	.1415	.1819	.1834	-0.82	.1827	-0.44	.1847	-1.32	.1837	-0.98
15-1	.1429	.1862	.1861	-0.05	.1855	+0.38	.1874	-0.64	.1864	-0.11
14-1	.1430	.1863	.1863	0	.1857	+0.32	.1876	-0.69	.1866	-0.16
2-4	.1473	.1945	.1947	-0.10	.1941	+0.21	.1959	-0.72	.1950	-0.26
5-7	.1478	.1940	.1957	-0.87	.1950	-0.51	.1969	-1.47	.1960	-1.02
18-5	.1481	.1944	.1963	-0.97	.1956	-0.61	.1975	-1.57	.1966	-1.12
3-3	.1498	.1979	.1996	-0.85	.1989	-0.50	.2008	-1.44	.1999	-1.00
1-2	.1515	.2030	.2030	0	.2024	+0.30	.2042	-0.59	.2033	-0.15
7-3	.1536	.2079	.2071	+0.39	.2065	+0.68	.2083	-0.19	.2075	+0.19
6-5	.1611	.2213	.2223	-0.45	.2217	-0.19	.2234	-0.94	.2226	-0.58
9-7	.1613	.2226	.2227	-0.04	.2221	+0.23	.2238	-0.54	.2231	-0.22
8-1	.1637	.2278	.2275	+0.13	.2270	+0.35	.2287	-0.39	.2279	-0.04
5-1	.1638	.2291	.2277	+0.61	.2272	+0.84	.2289	+0.09	.2281	+0.44
16-2	.1655	.2328	.2313	+0.65	.2308	+0.87	.2325	+0.13	.2317	+0.47
15-7	.1732	.2479	.2475	+0.16	.2470	+0.36	.2486	-0.28	.2480	-0.04
5-2	.1790	.2594	.2599	-0.19	.2595	-0.04	.2610	-0.61	.2604	-0.38
1-1	.1922	.2902	.2891	+0.38	.2887	+0.52	.2901	+0.03	.2895	+0.24
3-2	.1943	.2941	.2938	+0.10	.2935	+0.20	.2948	-0.24	.2942	-0.03
3-4	.1985	.3046	.3033	+0.43	.3030	+0.53	.3044	+0.07	.3038	+0.26

Run No.	Head	Measured Flow	Harris Computed Flow	Harris Correction	Rehboch 1912 Computed Flow	Rehboch 1912 Correction	Fteley and Stearns Computed Flow	Fteley and Stearns Correction	Cline Computed Flow	Cline Correction
	Ft.	Cfs.	Cfs.	%	Cfs.	%	Cfs.	%	Cfs.	%
11-5	.1991	.3039	.3047	-0.26	.3044	-0.16	.3057	-0.59	.3052	-0.43
18-2	.2015	.3111	.3102	+0.29	.3099	+0.39	.3111	0	.3107	+0.13
4-3	.2079	.3240	.3251	-0.34	.3248	-0.25	.3260	-0.61	.3255	-0.46
12-1	.2106	.3327	.3313	+0.42	.3311	+0.48	.3321	+0.18	.3318	+0.27
13-1	.2107	.3326	.3315	+0.33	.3313	+0.39	.3326	0	.3320	+0.18
6-3	.2137	.3392	.3388	+0.12	.3387	+0.15	.3397	-0.15	.3392	0
16-7	.2198	.3541	.3533	+0.23	.3531	+0.28	.3546	-0.14	.3538	+0.08
11-2	.2201	.3554	.3543	+0.31	.3542	+0.34	.3552	+0.06	.3546	-0.23
1-1	.2252	.3671	.3665	+0.16	.3663	+0.22	.3675	-0.11	.3668	+0.08
2-5	.2285	.3768	.3750	+0.48	.3749	+0.51	.3757	+0.29	.3750	+0.48
6-7	.2293	.3744	.3767	-0.61	.3766	-0.58	.3777	-0.87	.3769	-0.66
8-1	.2385	.4028	.3996	+0.80	.3996	+0.80	.4006	+0.55	.3998	+0.75
17-5	.2389	.3984	.4005	-0.52	.4005	-0.52	.4016	-0.80	.4010	-0.65
7-1	.2402	.4073	.4037	+0.89	.4038	+0.87	.4019	+0.59	.4040	+0.82
6-2	.2414	.4063	.4070	0.17	.4071	-0.20	.4078	-0.37	.4073	-0.25
1-5	.2432	.4103	.4115	-0.29	.4116	-0.32	.4128	-0.61	.4118	-0.36
10-7	.2433	.4089	.4119	-0.73	.4119	-0.73	.4128	-0.94	.4121	-0.78
1-4	.2469	.4167	.4212	-1.07	.4213	-1.09	.4221	-1.28	.4213	-1.09
8-3	.2536	.4384	.4385	-0.02	.4387	-0.07	.4396	-0.27	.4386	-0.05
12-2	.2594	.4550	.4538	+0.26	.4540	+0.22	.4545	+0.11	.4537	+0.29
24-1	.2618	.4601	.4598	+0.07	.4600	+0.02	.4608	-0.15	.4599	+0.04
25-1	.2619	.4604	.4601	+0.07	.4603	+0.02	.4611	-0.15	.4602	+0.04
26-1	.2623	.4610	.4612	-0.04	.4614	-0.09	.4621	-0.24	.4613	-0.07
17-1	.2693	.4800	.4802	-0.04	.4804	-0.08	.4810	-0.21	.4802	-0.04
11-2	.2697	.4811	.4814	[illegible]	.4818	-0.15	.4823	-0.25	.4813	-0.04
10-1	.2757	.5002	.4976	+0.52	.4979	+0.46	.4985	+0.34	.4973	+0.58
11-1	.2757	.4990	.4976	+0.28	.4979	+0.22	.4985	+0.10	.4973	+0.34
12-5	.2777	.5018	.5035	-0.34	.5038	-0.40	.5045	-0.54	.5031	-0.26
9-1	.2810	.5135	.5123	+0.23	.5126	+0.18	.5131	+0.08	.5118	+0.33
7-2	.2814	.5109	.5136	-0.53	.5140	-0.60	.5148	-0.76	.5133	-0.47
2-7	.2845	.5234	.5224	+0.19	.5227	+0.13	.5234	0	.5218	+0.31
4-4	.2951	.5525	.5521	+0.07	.5525	0	.5532	-0.13	.5515	+0.18
13-2	.2993	.5629	.5640	-0.20	.5645	-0.28	.5651	-0.39	.5634	-0.09
9-3	.2997	.5567	.5654	-1.15	.5659	-1.27	.5664	-1.36	.5646	-1.04
16-5	.3118	.5985	.6005	-0.33	.6010	-0.42	.6018	-0.55	.5996	-0.18
8-2	.3194	.6094	.6110	-0.26	.6115	-0.34	.6121	-0.44	.6101	-0.11
3-5	.3176	.6191	.6177	+0.23	.6183	+0.13	.6187	+0.06	.6165	+0.42

Run No.	Head	Measured Flow	Harris Computed Flow	Harris Correction	Rehboch 1912 Computed Flow	Rehboch 1912 Correction	Fteley and Stearns Computed Flow	Fteley and Stearns Correction	Cline Computed Flow	Cline Correction
	Ft	Cfs.	Cfs.	%	Cfs.	%	Cfs.	%	Cfs.	%
18-7	.3204	.6282	.6262	+0.32	.6268	+0.22	.6273	+0.14	.6248	+0.54
16-1	.3208	.6294	.6267	+0.43	.6273	+0.33	.6276	+0.29	.6256	+0.61
17-1	.3209	.6283	.6271	+0.19	.6277	+0.10	.6283	0	.6259	+0.38
18-1	.3209	.6274	.6271	+0.05	.6277	-0.05	.6283	-0.14	.6259	+0.24
5-3	.3232	.6336	.6346	-0.16	.6353	-0.27	.6356	-0.31	.6332	+0.06
28-1	.3236	.6357	.6352	+0.08	.6358	-0.02	.6366	-0.14	.6339	+0.28
27-1	.3238	.6360	.6355	+0.08	.6362	-0.03	.6366	-0.09	.6339	+0.33
8-5	.3252	.6378	.6406	-0.44	.6412	-0.53	.6415	-0.58	.6391	-0.20
7-7	.3345	.6644	.6685	-0.61	.6693	-0.73	.6700	-0.84	.6672	-0.42
5-4	.3356	.6724	.6720	+0.06	.6728	-0.06	.6733	-0.13	.6706	+0.27
22-7	.3379	.6786	.6791	-0.07	.6799	-0.19	.6803	-0.25	.6776	+0.15
14-2	.3393	.6825	.6837	-0.18	.6845	-0.29	.6849	-0.35	.6818	+0.10
11-7	.3423	.6928	.6929	-0.01	.6936	-0.12	.6942	-0.20	.6910	+0.26
13-5	.3504	.7171	.7184	-0.18	.7192	-0.29	.7196	-0.35	.7162	+0.13
9-2	.3562	.7345	.7365	-0.27	.7373	-0.38	.7378	-0.45	.7344	+0.01
3-7	.3773	.8051	.8049	+0.02	.8058	-0.09	.8064	-0.16	.8020	+0.39
15-2	.3792	.8089	.8110	-0.26	.8119	-0.37	.8130	-0.50	.8082	+0.09
23-7	.3810	.8170	.8171	-0.01	.8180	-0.12	.8186	-0.20	.8141	+0.36
15-5	.3874	.8369	.8385	-0.19	.8395	-0.31	.8398	-0.35	.8351	+0.22
6-4	.3907	.8487	.8493	-0.07	.8503	-0.19	.8514	-0.32	.8461	+0.31
4-5	.3963	.8699	.8683	+0.18	.8693	+0.07	.8699	0	.8647	+0.60
10-2	.4000	.8770	.8808	-0.43	.8819	-0.56	.8832	-0.70	.8771	-0.01
10-3	.4007	.8788	.8830	-0.48	.8841	-0.60	.8851	-0.71	.8795	-0.08
8-7	.4016	.8857	.8862	-0.06	.8874	-0.19	.8885	-0.32	.8826	+0.35
9-5	.4048	.8955	.8974	-0.21	.8985	-0.33	.8994	-0.43	.8934	+0.24
25-7	.4065	.9018	.9032	-0.15	.9042	-0.27	.9050	-0.35	.8992	+0.29
19-7	.4107	.9125	.9175	-0.54	.9186	-0.66	.9196	-0.77	.9135	-0.11
12-7	.4113	.9206	.9197	+0.10	.9207	-0.01	.9219	-0.14	.9156	+0.55
4-7	.4223	.9565	.9579	-0.15	.9590	-0.26	.9603	-0.40	.9536	+0.30
14-5	.4238	.9604	.9634	-0.31	.9644	-0.41	.9659	-0.57	.9587	+0.18
20-7	.4287	.9822	.9807	+0.15	.9817	+0.05	.9834	-0.12	.9759	+0.65
26-7	.4369	1.0105	1.0100	+0.05	1.0111	-0.06	1.0129	-0.24	1.0048	+0.57
24-7	.4501	1.0563	1.0579	-0.15	1.0590	-0.25	1.0609	-0.43	1.0522	+0.39
27-7	.4695	1.1306	1.1297	+0.08	1.1308	-0.02	1.1334	-0.25	1.1231	+0.67
30-7	.4779	1.1637	1.1615	+0.19	1.1628	+0.08	1.1655	-0.15	1.1544	+0.81
28-7	.4799	1.1676	1.1688	-0.10	1.1700	-0.20	1.1731	-0.47	1.1619	+0.49
21-7	.4829	1.1799	1.1805	-0.05	1.1816	-0.14	1.1848	-0.41	1.1732	+0.57
29-7	.4966	1.2315	1.2333	-0.15	1.2346	-0.25	1.2377	-0.50	1.2254	+0.50

CONCLUSION

The experimental results presented in this bulletin need extension to wider flumes, weirs of other heights, and higher heads It is hoped that further test data by other experimenters can be made available, with volumetric or gravimetric measurement of flow, which will advance the study and development of standards of weir construction

A flume 2 ft. wide, 3 ft deep and 20 ft long, with a 6-ft. glass section is being built in the hydraulic laboratory of the University of Wisconsin This flume will be used, among other things, for a continuation of sharp-crested weir studies

The study of original publications which the writer made in preparing this bulletin, together with the general uniformity of test results obtained in the State College of Washington laboratory, even with inexperienced student investigators, indicate to the writer that the conflicting statements and formulas about weirs which have been made and continue to be made in new books arise less from the inherent inaccuracy of the sharp-crested weir itself than from lack of standards of construction of the early investigators, as well as inaccuracies in technique and insufficient number of tests

Acknowledgement

Many students at the State College of Washington have had a part in obtaining the data of these weir tests. The design and supervision of the construction of the flume were mainly the work of E. Kinzel, C.E., 1931 N.Y.A students during the past two years contributed materially by computing tables for the various formulas which greatly lightened the labor of computation of the test results.

The Hydraulic Laboratory is under the direction of H. V Carpenter, Dean of the College of Engineering, and of M K. Snyder, Head of the Department of Civil Engineering, through whose efforts funds for the construction of the weir flume were obtained.

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No. 3. PHYSICAL CHANGES ACCOMPANYING THE AGING OF A MAGNESIUM ALLOY

By James G. McGivern

Assistant Professor of Mechanical Engineering

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(b) The change in yield strength (.20% set) is not a constant for all annealing temperatures but increases as the aging temperature decreases. The change in yield strength for 300°F. aging is from 32,500 lbs./sq." to 40,750 lbs./sq." whereas for the 420°F. treatment the corresponding change is from 32,100 lbs./sq." to 34,000 lbs./sq.".

(c) The rate of aging increases with the aging temperature and with the initial hardness.

(d) The fracture pictures and the micro-structures reveal the mechanism of aging and the preferred orientation of the crystals resulting from the original extrusion process.

II. By aging from the extruded condition at temperatures from 300°F. to 420°F. it is possible to change the strength, hardness and ductility for the alloy investigated The rate of aging from this strained state is considerably faster than when aging follows annealing.

(a) By aging from two to ten hours it is possible to increase the percentage reduction of area from 12% to 32% and the percentage elongation in two inches from 12% to 23%.

(b) Aging for times greater than that time corresponding to maximum reduction and elongation causes a decrease in ductility accompanied by an increase in strength.

(c) The increase in maximum strength is not near as great as for aging following annealing and very little increase in yield strength was recorded.

Physical Changes Accompanying The Aging Of A Magnesium Alloy

By James G. McGivern

INTRODUCTION

Since the work of Merica, Waltenberg and Scott[1] on the heat treatment of duralumin, considerable attention has been focused on alloy systems exhibiting aging possibilities. These systems have the common property that the amount of the alloying element soluble in the solid parent metal decreases with temperature and that the rate of separation of this excess constituent is slower than ordinary quenching rates. For alloy systems whose equilibrium diagrams have been determined it is possible to tell by the slope of the line showing the change in solid solubility whether or not aging is possible. For those alloy combinations whose equilibrium relations have not been established it is possible to determine whether they may be expected to show aging by applying certain principles involving the ratio of the atomic diameters of the elements involved[2]

It has been established that the solid solubility of aluminum in magnesium varies with temperature and that alloys of magnesium containing more than seven per cent of aluminum are capable of aging Specific data on the actual changes in strength and ductility accompanying aging are, however, lacking.

The purpose of this paper is to present the results of aging on the tensile properties of an extruded magnesium alloy containing 8% aluminum The effect of aging from the extruded condition, from a partially annealed and from a completely annealed condition are included. For each test the usual values of maximum strength, breaking strength, yield strength (.20 permanent set), hardness, percentage elongation in two inches, and percentage reduction in area are reported. In addition the yield strength (.10% permanent deformation), Johnson's limit, stress corresponding to specified sets, true elongation in two inches, and the true breaking stress on the basis of the breaking load and the reduced diameter are also given.

[1] Merica, P. D , Waltenberg, R. G., and Scott, H., "Heat Treatment of Duralumin," Bulletin Am. Inst. of Mining Eng., p. 913, June 1910.

[2] Hume-Rothery, W., "The Structure of Metals and Alloys," Monograph and Report Series No. I. British Institute of Metals, 1936.

PRINCIPLE OF HEAT TREATMENT

The heat treatments given this alloy prior to testing are those previously investigated, using hardness as an index of change in physical properties.[3] These treatments are based on the fact that the amount of aluminum soluble in magnesium in the solid state varies with temperature. By controlling the solubility relationships between the aluminum and magnesium it is possible to change the physical properties. The equilibrium diagram[4] of Fig. 1 shows that all the 8% of the aluminum is soluble above a temperature of approximately 600°F., while at room temperature the solubility is 7%. Authors[5] differ as to the solubility at room temperature and quote values from a minimum of 2% up to the 7% quoted. Any ordinary rate of quenching from a temperature represented above the line ab of Fig. 1 will

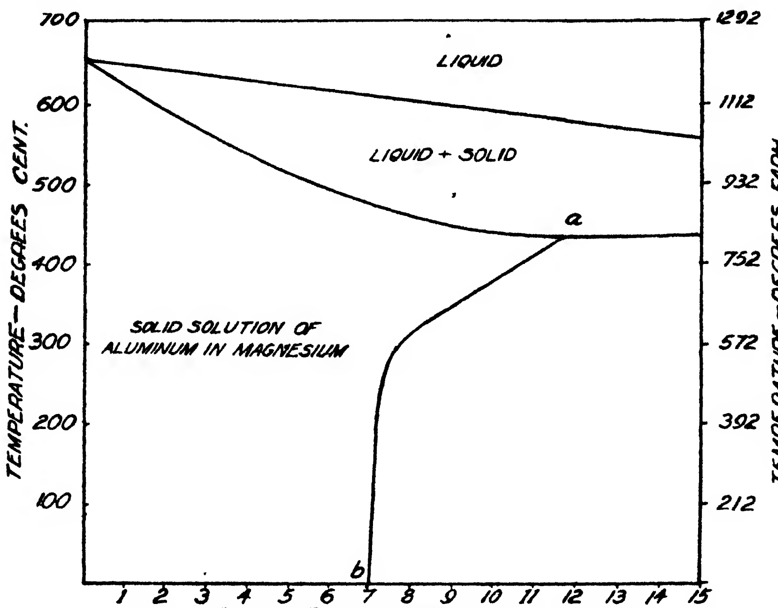


Fig. 1. Magnesium rich portion of magnesium aluminum series.

[3] McGivern, J. G., and Wilkinson, C. A., "Precipitation Hardening of a Magnesium Alloy Containing 8% Aluminum," Washington State College Engineering Experiment Station, Bulletin No. 50, July 1937.

[4] Schmidt and Spetaler, Jr. Inst. of Metals, Vol. 34, p. 195.

[5] Bokken, H. F. and Wood, R. T., "Constitution of Magnesium Aluminum Alloys," Metals Handbook, 1936 edition.

be faster than the rate of separation of the aluminum from the magnesium. Because of this, the quenched metal contains an excess of aluminum in solution and is unstable. The metal if then heated, to relative low temperatures represented below the line ab of Fig. 1 will allow this excess aluminum to precipitate as part of the hard intermetallic compound Mg_3Al_2 and cause the physical properties to change. The lower part of line ab being practically vertical means that the reheating or aging temperature may be as high as 500°F. without appreciably changing the solubility relation, and hence the amount of super saturation. As the metal is heated to this temperature, however, its viscosity decreases and hence the ease with which the intermetallic compound may form and ease of diffusion also increases. By heating to temperatures between 500°F. and 600°F. aging is still possible. Fig. 1 shows the solubility changes within this range This decreases the amount of super saturation or the urge to age even though the opportunity to precipitate at the higher temperature may be more favorable. All this suggests the following heat treatment:

(1) Heating metal for a sufficient time at a high enough temperature to relieve any strain hardening and cause all the aluminum to be in solid solution with the magnesium

(2) To quench from this temperature at a faster rate than that of the separation of the aluminum from the magnesium

(3) To heat to certain low temperatures to allow the aluminum to precipitate from the magnesium and form the hardening constituent Mg_3Al_2 at a controlled rate.

The extruded material in the "as received" condition has been worked at a temperature sufficiently high to cause most of the aluminum to be in solid solution and yet the final working temperature was not high enough to entirely relieve the grains of the working effects. This condition makes possible an aging treatment of the strained material without a preceding high temperature anneal. In this treatment the material is heated to temperatures represented below the line ab of Fig 1 and gives a combination strain relief and precipitation.

The material may also be aged from a partially annealed condition This treatment is similar to the first treatment described, with the exception that the time of the high temperature anneal is shortened

By varying the time of this anneal various conditions between completely strain hardened and complete solution equilibrium may be obtained for the beginning of the aging treatment.

Aging Following a Complete Anneal

Anneal. The specimens prior to aging were annealed at 775°F for eighteen hours. The changes in physical properties and in micro-structures accompanying this preliminary treatment have been presented in an earlier bulletin as well as a complete description of the physical tests and measurements used[6] As before, rods having different initial

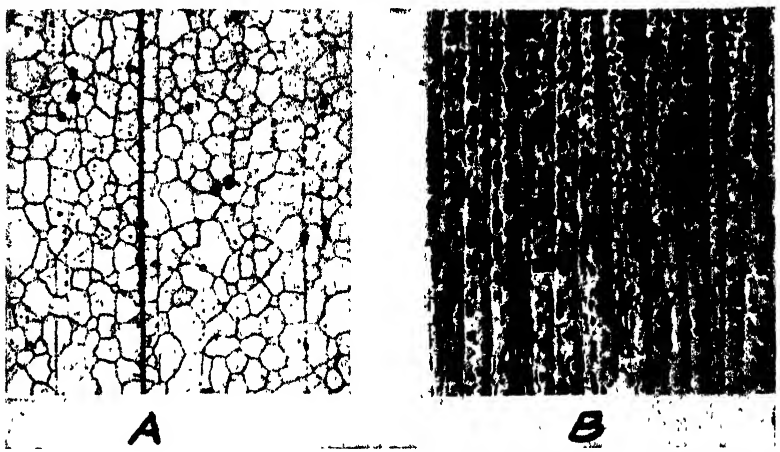


Fig 2 Difference in micro-structures of rods having different initial hardnesses. Specimen A (65 Rockwell E) and B (69.-71 Rockwell E) 100X.

hardnesses were used and the same annealing time produced different degrees of strain relief on specimens represented by A and B of Fig. 2

For both cases the material on being quenched from 775°F. was super saturated with aluminum and its micro-structure showed no visible precipitation. Very little, if any, grain growth was evident following the recrystallization which took place with the annealing.

Changes in Physical Properties. The changes in physical properties with aging time for the 300°F., 370°F, and 420°F. aging are given

[6] McGivern, J. F., "Physical Changes Accompanying High Temperature Anneal of a Magnesium Alloy," Washington State College, Eng. Exp. Sta., Bulletin No. 52, Jan., 1938.

in Fig. 3 and Table 1. Fig 3 gives the usual values of maximum strength, yield strength (.20% set), percentage elongation in two inches, percentage reduction in area and the hardness prior to testing. The tables give in addition the final hardness after testing, the yield strength (.10% set), Johnson's Yield, and the stresses causing yields of 70%, .75% and .85%. The true stress at failure which is the breaking load divided by the final area is also recorded along with the breaking strength, which is the breaking load divided by the the original area The maximum strength or the maximum load divided by the original

TABLE 1

500°F Aging Following 18 Hrs at 775°F														
No.	Time	Initial Hardness	Final Hardness	% Elong.	% Red.	.1% Yield	.2% Yield	Johnson's Yield	Stress at .7% Yield	Stress at .75% Yield	Stress at .8% Yield	Maximum Strength	Stress on Orig. Area at Failure	Stress on Final Area at Failure
219	16	61.1	70.5	9.1	9.55	32100	35250	26000	32100	33400	34350	45400	45400	50100
220	36	69.6	76.5	7.5	8.9	36500	38250	32750	35500	36350	37100	47000	47000	51600
221	45	75.5	78.0	5.5	5.1	38000	39750	35250	34900	36000	37100	50500	50800	53200
222	45	74.5	79.1	4.7	4.6	38100	38750	35700	38250	39000	39500	50400	50400	52900
223	50	76.5	80.9	1.6	2.0	37400	39000	35250	36000	37000	38850	50000	50000	51300
224	51	76.5	79.7	6.6	6.5	36850	38400	35250	35500	36000	38150	48500	48500	51900
225	52	76.8	80.2	4.7	5.0	39350	39800	34250	34500	36000	37500	52500	52500	56000
226	60	78.0	80	3.4	4.2	39600	40300	37250	37600	38700	39250	51100	51100	53800
227	70	78.5	80.7	4.24	4.0	37500	40750	34750	36750	38000	39100	53800	53800	55700

370°F Aging Following 18 Hrs at 775°F															
No.	Time	Initial Hardness	Final Hardness	% Elong.	% Red.	% Unit Elong.	.1% Yield	.2% Yield	Johnson's Yield	Stress at .7% Yield	Stress at .75% Yield	Stress at .8% Yield	Maximum Strength	Stress on Orig. Area at Failure	Stress on Final Area at Failure
250	0	54.6	70.2	10.9	13.7	16	31750	33400	28750	32000	32350	32850	42800	44500	45500
251	7	57.1	72.5	10.5	11.6	13.7	32000	32850	29000	31750	32250	32500	44300	44300	50400
252	22½	66.6	74.5	6.6	6.14	9	36750	40000	34250	34250	36000	37500	45500	45500	47500
253	30½	71.5	75.0	3.5	3.0	5.5	38000	37000	35000	34250	35250	36000	47700	47700	50600
254	40½	73.2	78.0	4.7	2.9	4.5	34000	35500	29500	34500	36000	35600	48600	48600	51000
255	67½	75.3	79.5	6.2	7.0	7.5	34250	36500	31250	33750	34750	35600	51300	51300	56000
256	90	75.6	78.0	4.7	4.7	5	36000	37500	32500	32500	34000	35000	51500	51500	54000
257	114	78.5	80.5	2.5	3.2	3.25	35000	36750	32500	34500	35350	36250	49700	49700	51700

420°F Aging Following 18½ Hrs at 775°F																	
No.	Time	Initial Hardness	Final Hardness	% Elong	% Red.	% Unit Red.	% Unit Elong	.1% Yield	.2% Yield	Johnson's Yield	Stress at .7% Yield	Stress at .75% Yield	Stress at .8% Yield	Stress on Orig. Area at Failure	Stress on Final Area at Failure	Stress on Unif. Area at Max. Load	Maximum Str.
409	0	62.4	77.6	17	14.8	11.8	18.5	30750	32100	26500	32500	32650	33200	45000	52750	51600	45500
415	10;10	76.3	81.5	9.0	10.2	7.7	11.5	34150	35700	30250	34100	34900	35400	48900	54500	53000	48900
414	24	79.9	78.5	2.5	3.1	1.4	3.0	34000	35500	30250	34650	35200	35750	47800	49400	48600	47800
413	46¼	80.5	79.8	4.0	3.9	2.14	4.0	33000	34350	29600	34000	34500	35000	48900	51000	50100	48900
412	71¼	80.2	82.5	6.0	5.9	5.10	6.7	34800	36000	30750	35200	35750	36250	52500	56300	55400	52500
416	121¾	79.1	81.5	2.5	3.28	2.40	3.2	31650	33000	28250	32150	33150	33700	47300	48900	48300	47300
417	171	79.0	80.0	3.0	3.8	.60	4.0	32500	33750	26750	33000	33500	34000	45750	47600	46000	45750
418	239	78.8	79.8	3.5	3.8	3.06	4	31800	33400	28000	32500	33000	33800	50000	52100	51600	50000
419	309	79.3	81	2	2.5	1.56	2.5	32850	34000	29750	33500	33650	34250	45500	46750	46400	45500

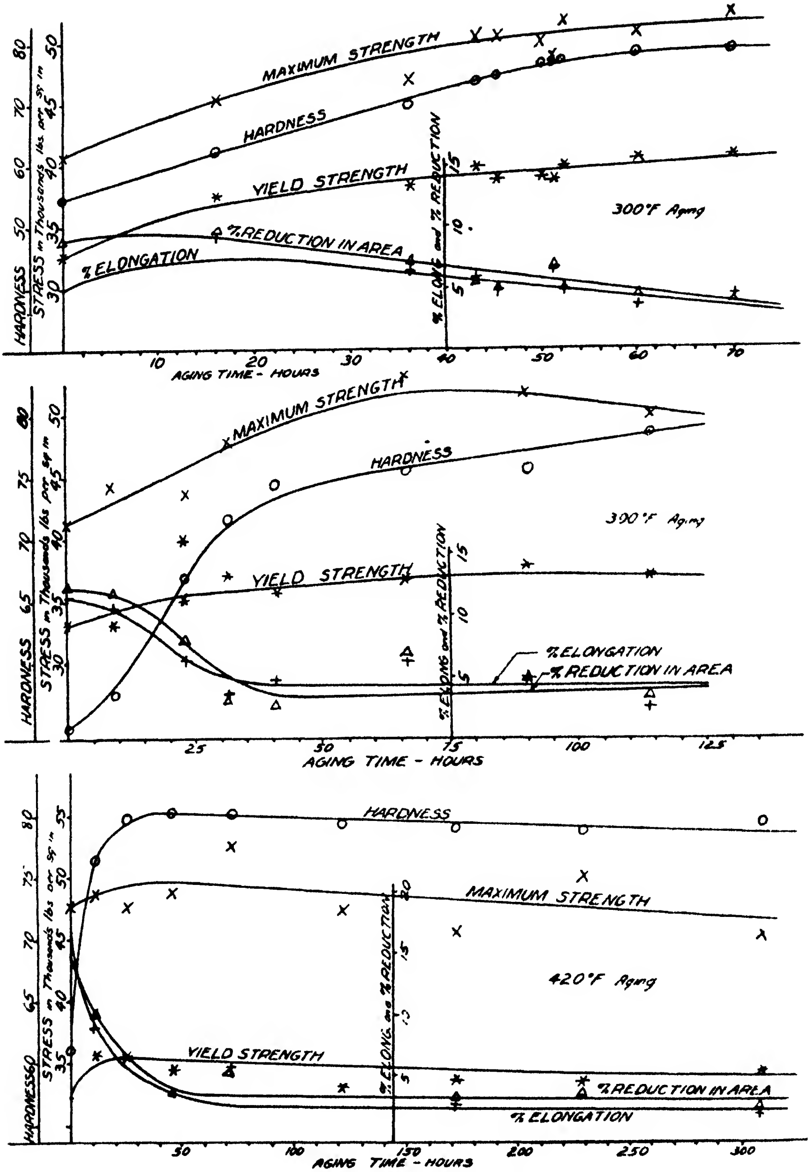


Fig. 3. Physical properties accompanying aging at 300°F, 390°F, and 420°F following an anneal.

area and, in some cases, the maximum load divided by the uniformly reduced area removed from the necked section is given.

A comparison of the effects of the different aging temperatures on the rate and final results of aging is shown in Fig 3 For the three temperatures given the rate of aging increases with the aging temperature The initial condition of the three cases are not the same. This is best illustrated by the high initial hardness of 62 Rockwell E for the 420°F as compared to the 55 Rockwell E value for the 370°F. and the 300°F. curves The difference is due to the difference in the original extruded rods before annealing, which is illustrated in Fig. 2.

The values for the lower temperature appear to follow closer to an average curve than for the 420°F aging The highest maximum strengths obtained for the three treatments are 53,800 lbs./sq ", 54,100 lbs /sq ", and 52,250 lbs /sq " respectively The average maximum as represented by the curves is approximately 52,000 lbs /sq " and is the same for the three cases These values correspond to a percentage reduction in areas and percentage elongation of 5% This change in strength with time is accounted for by the increasing amount of the precipitated intermetallic compound Mg_3Al_2 which separates out from the super saturated solid solution As more and more of this hard constituent forms, the resistance to slip increases and the metal becomes stronger, harder and more brittle In addition to the evidence afforded by an examination of the change in micro-structure with time, the types of fracture show a gradual change from a combination shear and tension failure to one of practically pure tension as given in Fig 4.

The percentage increase in the value of the yield strength resulting from aging is not nearly as great as the percentage increase in maximum strength The average value of the increase in maximum strength due to the three aging temperatures is 20 8% as compared to 12 0% for the corresponding increase in yield strength. This is not always true as work has been done[7] on the aging of cast magnesium showing a greater percentage increase in the yield strength than in the maximum strength. The maximum yield strength attainable is not the same for the various aging temperatures but decreases as the aging temperature increases The maximum yield strength values are 40,750,

[7] Lyon, A. J., "Stability of Aluminum and Magnesium Castin Alloys," Am. Inst. of Min. and Met. Eng.," Inst of Metals Darwin, p 336, 1929.

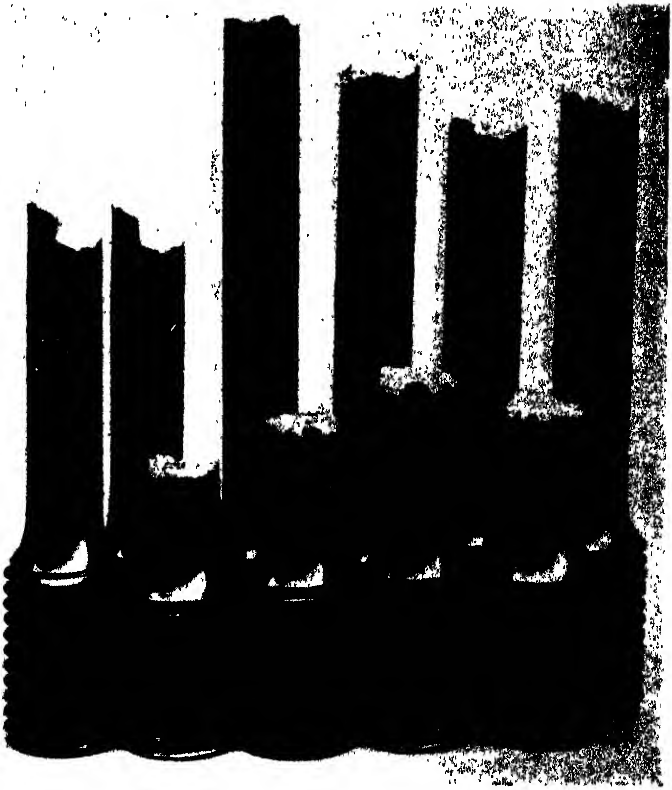
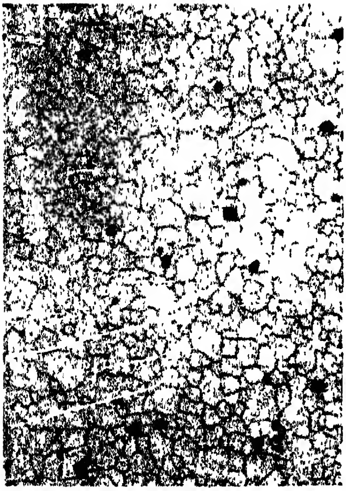


Fig 4 Fracture pictures for 420°F aging following a 775°F anneal The specimens, reading left to right, have been aged 0, 10, 24, 48 and 171 hrs respectively

37,500 and 36,000 lbs/sq" for the 300°F, 370°F and 420°F. aging temperatures respectively This means the lower the aging temperature the better the final product as reflected by the high yield strength, the other properties being the same.

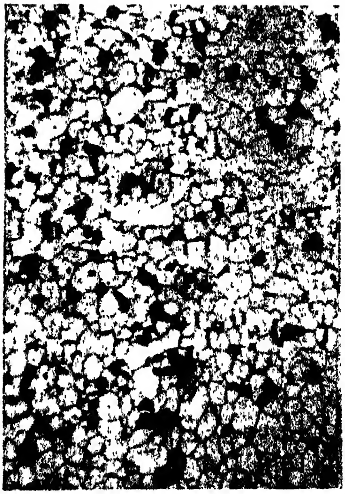
Changes in Micro-structures. The micro-structures represented in Fig. 5 illustrate some of the more important changes accompanying the 370°F. aging. The etching of the material following the 775°F annealing and prior to aging was very ineffective. After as short an aging time as twenty minutes the grain structure was clearly revealed



A

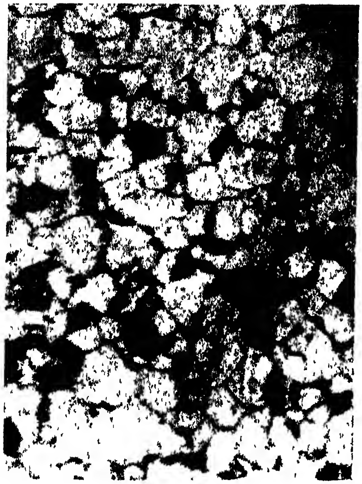
B

C



D

Fig. 5. Changes in micro-structures for 370°F. aging following 775°F anneal Specimens A, B, C and D have been aged 2, 5, 9¾ and 16½ hrs respectively. Longitudinal sections 100X.



E

F

G

Fig. 5 Changes in micro-structures for 370°F aging following 775°F anneal. E and F are perpendicular sections aged 16½ hrs. 200X. G has been aged 19 hrs. Longitudinal section 2000X.

but the etching time for the 2% oxalic acid solution used was much longer than just the swab needed on specimens aged a longer time Although the ease of revealing the grain structure increased with the aging time no distinct precipitated areas were observable for the first few hours although the hardness and percentage elongation in length and reduction of area do change during this time

The micro-structures in addition to revealing the mechanism of precipitation throw considerable light on some of the changes which took place in the preliminary annealing treatment The rod as originally formed was plastically deformed in the extrusion process, the amount of strain being greatest for the outside section of the rod This means that the time necessary for recrystallization to take place at a given temperature will be a minimum at the outer surface and increase for sections nearer the center Following the recrystallization coalescence will take place as evidenced by grain growth although in this case the average grain size is very little different from the original size as sufficient time was not allowed for changes to take place[8] Fig 5A and 5B illustrate this condition These micro-structures were taken from two different positions of their respective rods

Fig 5A shows a section from a rod that was aged two hours This micro-structure represents a section of uniform grain size and shows no visible precipitated areas Fig 5B represents a section near the outside of a rod that was aged five hours, and shows grain growth which took place with the preliminary annealing process Near the center of this same rod no grain growth was evident A more striking example of this phenomena may be seen by comparing the micro-structures taken from sections perpendicular to the axis of extrusion These are given in Figs 5E and 5F which are both taken from the same rod Fig 5E which was taken near the outside of the rod, shows no twinning, while 5F near the center, shows considerable twinning The presence of annealing twins in magnesium is not unusual as it twins quite easily,[8] but its twinning on the cross-section only is unusual

This twinning being plainly visible on the plane perpendicular to the axis of extrusion and being rarely seen on the plane parallel to the axis, is explained in terms of the crystal structure and working of

[8] Mathewson, C H, "Twinning in Metals," A I M E (1928) 554

magnesium. Magnesium has a close packed hexagonal space lattice which below a temperature of 225°C. has only one plane of easy slip. This slip takes place along the basal planes, and in the extrusion process the basal planes align themselves in the direction of flow but are arranged in all orientations about the extrusion axis as an axis of rotation.[9] This preferred orientation of the crystals in the rod and there being one twinning plane, explains twinning being seen in Fig. 5F but not in Fig. 5E.

The increase in the amount of the precipitated area for the first sixteen and one-half hours is seen by comparing Figs 5A, B, C and D. This change is accompanied by an increase in hardness, maximum strength and yield strength, and by a decrease in percentage reduction in area and percentage elongation in two inches as given in Fig. 3. Beyond this time the amount of the precipitated area steadily increases, accounting for the further increase in strength and loss in ductility. This precipitation of the inter-metallic compound Mg_3Al_2 is first evident at the grain boundaries and in practically all cases the dark precipitated areas shown in Fig. 5 start at the grain boundaries. These areas have a definite structural form and the aggregate made up of the precipitated Mg_3Al_2 particles imbedded in the solid solution of the aluminum in magnesium are evidently harder and stronger than the plain saturated or super saturated solid solution of Al in Mg. For longer aging times than those represented in the micro-structures of Fig. 5E and 5F there appears to be a uniform precipitation of the inter-metallic compound within all the grains, in addition to the more dense areas which have been referred to. This is illustrated in Fig. 5G This is not true for specimens aged from the extruded conditions and it may account for the increased strength attained by these specimens when aging follows annealing, as compared with those aged from the extruded condition. A comparison may be had by comparing micro-structures of Fig. 5G with Figs. 9 and 10 and also the curves of Fig. 3 with those of Fig. 6.

AGING FROM THE EXTRUDED CONDITION

Changes in Physical Properties. The material in the "as received" condition varied in hardness from 65 to 69 Rockwell E. The micro-

[9] Morell and Hanawlt.................... ......Physics, 1932, 3, 161.

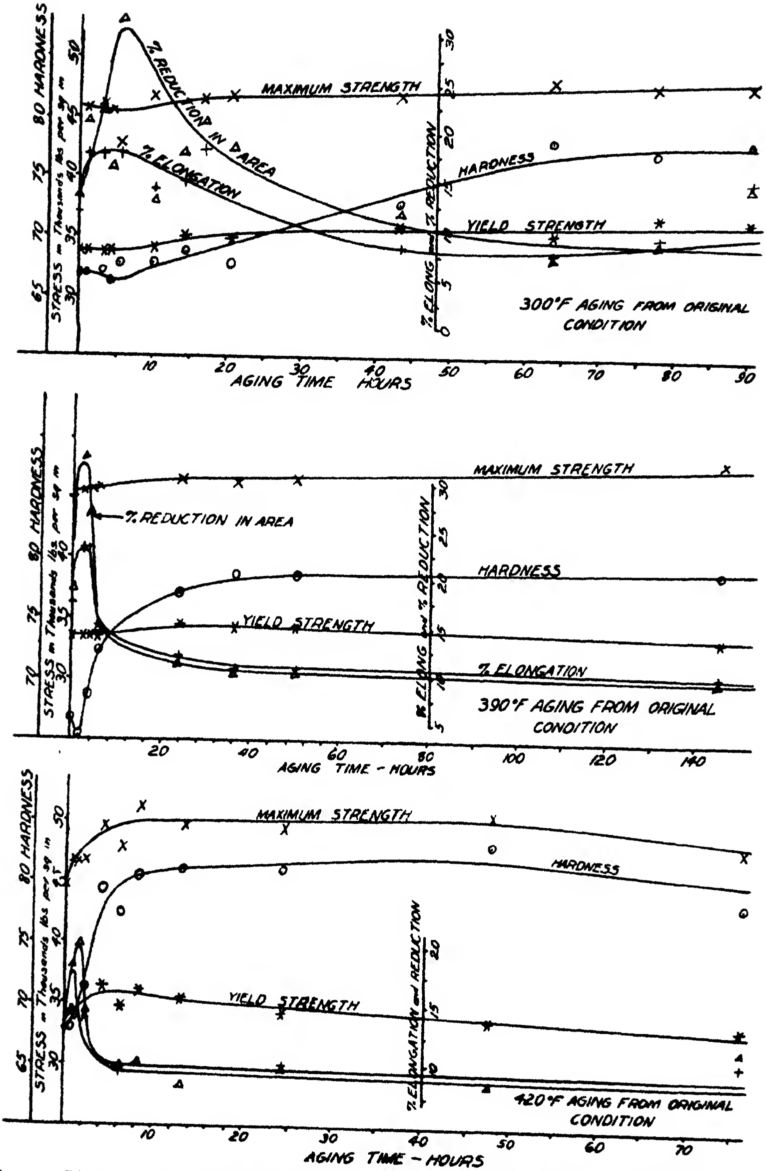


Fig. 6. Physical properties accompanying aging at 300°F., 390°F. and 420°F. from the extruded condition.

structures corresponding to this hardness range varied as to the amount of visible precipitate, the two extremes being given in Fig. 2.

The changes in the physical properties accompanying the 300°F., 390°F. and 420°F. aging are given in Fig. 6 and Table II. The chief difference between the curves given for the various aging temperatures is due to the increase in the aging rate rather than the general character of the changes and the final results obtained. A comparison between the 300°F. aging and the 390°F aging shows that the rate of aging, as measured by hardness and strength, increases with temperature in this range. This is to be expected as Fig. 1 shows little, if any, change in the solubility up to the 390°F. which means that the unstable condition caused by the extrusion process can more quickly approximate equilibrium conditions at the higher temperature with its correspondingly lower viscosity There is a limit to the upper temperature which will further increase this aging rate. This limit is caused by the change in solubility with temperature which means that the degree of instability decreases even though the opportunity to adjust itself increases One extreme of this is given in the results of aging at 600°F from the extruded condition as given in the preceding bulletin of this series Aside from the initial changes taking place which are due to the recrystallization, this test showed very little if any aging effects

The 420°F aging given in Fig. 6 shows a faster rate than either the 300°F. or the 390°F. treatment but the difference cannot be attributed entirely to the temperature difference In this case the original hardness was not the same, which may account for part of this difference.

These tests on the aging of the material from the worked condition show a combination of strain relief and precipitation hardening taking place simultaneously In the three tests represented in Fig. 6 the first five hours show characteristic loops in the aging curves. During this period the percentage elongation and reduction in area reach a maximum value which for the 390°F. treatment is as high as 32% for the reduction in area and 23% for the elongation in two inches. This materially betters the ductile characteristics of the metal without appreciably lowering the maximum strength or the yield strength from its original value.

TABLE II

300°F Aging From the Extruded Condition														
No.	Time	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	.1% Yield	.2% Yield	John-son's Yield	Stress at .7% Yield	Stress at .75% Yield	Stress at .8% Yield	Maximum Strength	Stress on Orig. Area at Failure	Stress on Final Area at Failure
200	0	66.8	76.3	12.0	13.6	32750	33500	30500	33000	33800	33600	45900	45800	53000
201	1½	66.8	70.8	17.5	21.5	32600	33400	29500	32750	33100	33400	45800	45800	55800
202	3	67.0	80.2	17.5	21.6	32000	33400	28750	32250	32750	33500	46060	44200	51600
203	4	65.8	78.3	15.0	16.3	32400	33500	29250	32500	32850	33550	45250	44600	53400
204	5¼	67.7	69.0	17.5	32	30250	31150	27500	30500	30750	31100	42000	40300	60100
205	10	67.5	79.8	14.0	12.8	33250	34000	30250	31750	32750	33350	46800	46100	52800
206	14½	68.6	78	15.0	17.6	34400	35000	32750	33250	34000	34500	46200	45500	56000
207	17	66.4	78	18.0	21.0	32500	33500	29500	32500	32850	33250	46300	45400	57500
208	20¾	67.5	79.3	16.0	18.3	34000	34900	31500	33750	34250	34750	46800	45400	55500
209	45	72.6	80.5	8.0	11.7	34250	35750	30750	33500	34350	35100	46900	47000	53200
210	64	77.9	81.4	7.5	7.4	33500	36000	29750	32500	35400	34000	48000	48000	51900
211	78½	76.8	79.8	9.0	8.7	33850	36500	30750	33250	34500	35500	47700	47800	52800
212	90	77.6	82.1	15.0	14.0	34750	36000	29600	35200	35750	36150	47720	47000	54700
213	118	78.0	82.3	7.5	8.6	35750	37500	32000	32750	33800	35000	49500	49500	54000
214	219	77.4	81.6	10.1	9.7	35500	37000	32750	33250	34500	35250	49600	49600	55200
215	358	77.2	82.4	6.0	7.6	35000	37200	31500	34000	35000	35750	50200	50200	51200

390°F Aging From Extruded Condition															
No.	Time	Initial Hard-ness	Final Hard-ness	% Elong.	% Red.	% Unit Elong.	.1% Yield	.2% Yield	John-son's Yield	Stress at .7% Yield	Stress at .75% Yield	Stress at .8% Yield	Maximum Strength	Stress on Orig. Area at Failure	Stress on Final Area at Failure
240	2	65.5	76.4	17.5	26.8	38.5	31750	33550	29000	31500	32000	32750	45000	42800	59000
241	3½	68.7	80.7	17.5	21.0	26.5	32600	33500	30000	32500	33000	33500	45700	43900	55500
242	5½	72.1	79.6	9.5	9.2	11	32500	33500	29500	32000	32500	33100	46000	46000	51200
243	24	77.0	80.5	6.5	5.8	16	33100	34500	29250	32850	36650	34000	46600	46600	54000
244	36½	78.5	78.0	5.5	5.1	5.5	33000	34250	30000	32750	33400	33750	46500	46300	48700
245	49	78.7	81.5	5.5	5.2	7	32750	34200	30000	32250	33000	33700	46800	46800	50000
246	145	79.0	81.5	7.0	6.7	7.8	32000	33500	30500	32250	32750	33250	48500	48500	52200

420°F Aging From Extruded Condition																	
Lo.	Time	Ini-tial Hard ness	Final Hard-ness	% Elong.	% Red.	% Unif Red.	% Unit Elong.	.1% Yield	.2% Yield	John-son's Yield	Stress at .7% Yield	Stress at .75% Yield	Stress at .8% Yield	Stress on Orig. Area at Failure	Stress on Final Area at Failure	Stress on Unif. Area at Max. load	Max. Str.
401	0	67.8	75	9.5	11.8	5.58	14	31150	33200	25000	33200	33600	34000	43400	49200	48700	44800
408	½	67.8	80.3	17.5	17.9	12.5	22	33200	34350	27750	23800	34250	34500	46200	56300	53500	47000
406	1	68.8	78.4	16.5	20	8.61	24.5	33200	34250	29000	33800	34250	34650	45400	56500	50900	46500
407	2	71.1	79.8	12	14.5	10.2	17.0	32900	33650	28850	33750	34250	34700	46800	54900	52100	46800
400	4	79.2	84.5	9.0	9.1	7.98	10.5	34000	36150	29000	34250	35000	35850	49700	55000	54000	49700
405	6	77.1	83	9	9.8	8.25	11.0	33250	34500	29250	34100	34500	34850	47800	53000	52100	47800
402	8	80.5	84	10	10	7.61	12.0	34350	35900	30000	35750	36200	36700	51500	57400	55500	51500
403	13	81	85.9	8	8.1	6.15	9.0	33450	35200	29250	34150	34700	35300	49600	53900	52800	49600
404	24	81.2	85.5	10	9.7	8.0	11.05	32700	34250	29000	33300	33850	34200	49600	54900	54000	49600
410	47½	85.7	87.2	8	8.1	7.05	9.0	32350	33750	28500	33400	33850	34250	51000	55500	55000	51000
411	77	78.5	84.5	11	12.1	10.3	14.0	32250	33250	28500	32900	33550	33850	48250	54900	54100	48500

This combination of strain relief and precipitation hardening taking place at the same time accounts for this maximum occurring With the beginning of aging precipitation also starts which would, if acting alone, make the percentage reduction and percentage elongation decrease The softening and the general increase in ductility accom-

panying the strain relief more than offsets the hardening due to precipitation, and for the first part of the curve the result is an increase in ductility. After the curve reaches its peak the hardening effect of the precipitation is greater than softening accompanying the strain relief and the metal gradually becomes harder, stronger and less ductile. At this time the rate of change in physical properties is greater than that obtained when aging from the annealed condition as given in Fig. 3, although the maximum values obtained are not as great as may be seen by comparing Figs. 3 and 6. The average maximum strength in this case may be taken as 49,500 lbs./sq." and the corresponding yield strength as 35,300 lbs./sq.". In this case the maximum yield strength does not appear to vary much with the temperature of aging.

Fracture Pictures. The changes in the fractures with time of aging for the 420°F. treatment are given in Fig. 7. The fracture of the metal in the "as received" condition is a combination tension and shear failure with a square tension fracture in the center and a strong shear lip on the outside This tension fracture in the center was seldom circular but generally elliptical. The lip under these conditions did not extend entirely around the specimen but occurred on opposite sides. With the beginning of aging the shear fracture becomes more predominant until at the time corresponding to the maximum elongation the fracture is entirely a shear fracture as seen for the one hour specimen pictured in Fig. 7. This is a typical case and was the same for the other aging temperatures. After this maximum percentage elongation and percentage reduction in area has been reached the fracture changed very quickly and after a four-hour treatment the specimen fails in practically pure tension This change to a tension fracture is attributed to an increase in the shear resistance accompanying the precipitation which is illustrated by an examination of the micro-structures.

Changes in Micro-Structures. The changes in micro-structures for the 390°F. aging are given in Fig. 8. The first three structures A, B and C are longitudinal sections. The first one is in the "as received" condition and shows an extrusion stringer and a slight twinning effect. At the end of one-half an hour these stringers, although present, are not as well defined. Fig 8C shows that at the end of three and a

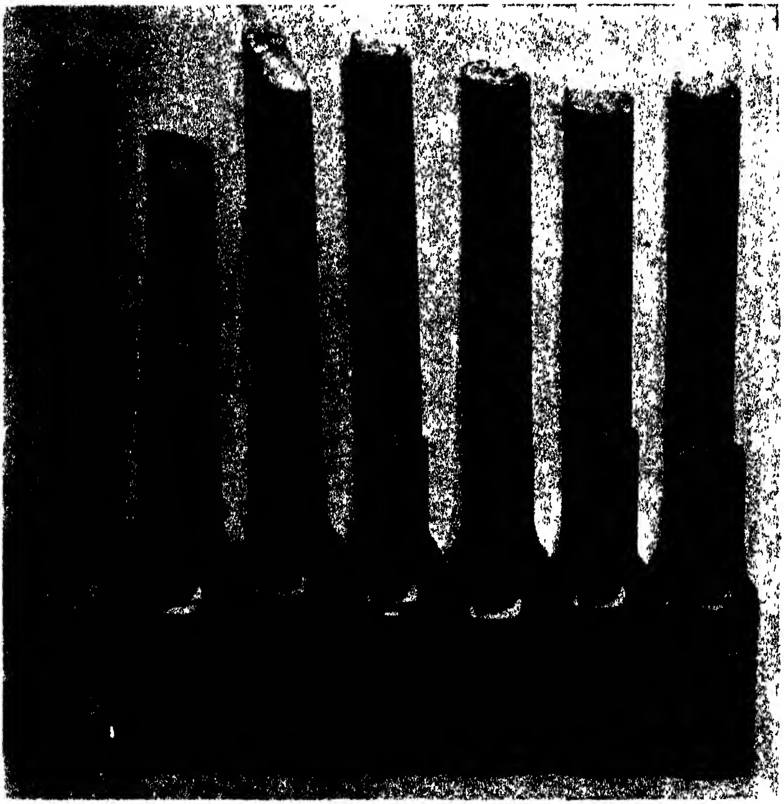


Fig 7 Fracture pictures for 420°F. aging from the extruded condition The specimens reading left to right have been aged 0, ½, 1, 2, 4, 16, and 79 hrs respectively

half hours the precipitated areas are clearly visible even though this does correspond to conditions of maximum ductility as seen in Fig. 6. Figs. 6D and 6E are photographs taken of perpendicular sections of this same specimen. Fig 6D was taken near the center of the specimen and shows no twinning, while 6E which was taken near the edge shows considerable twinning along with the precipitation. This difference in twinning between the outside and the center may be accounted for by the difference in residual strain in these sections associated with the original extrusion process. For the same temperature the outside, which is more severely strained, will recrystallize

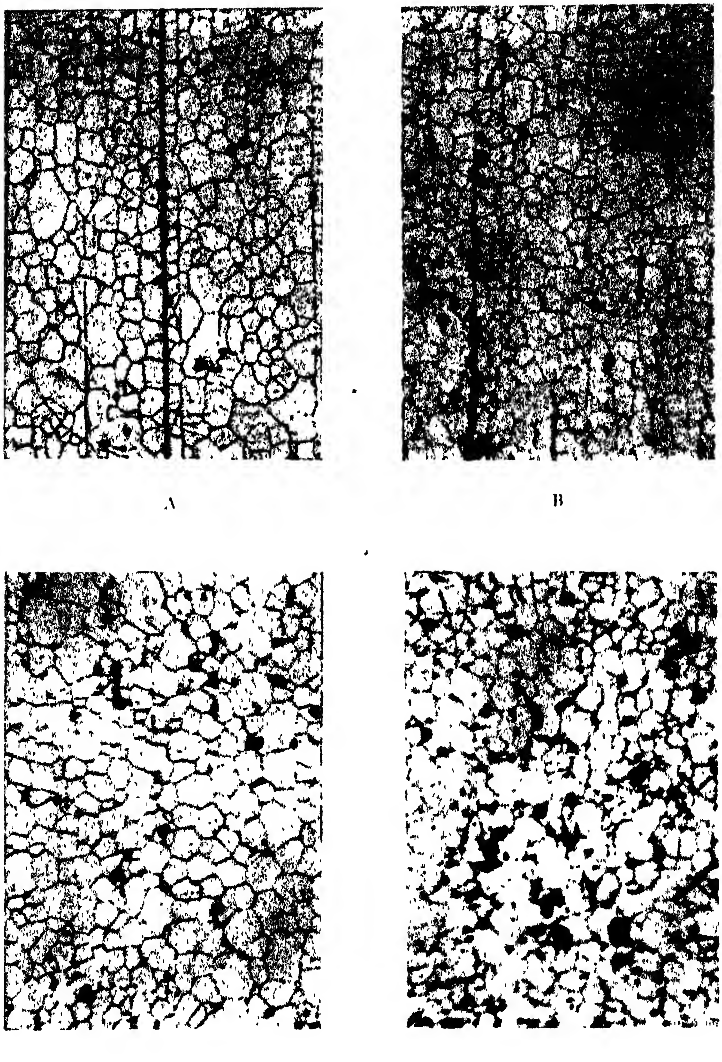


Fig. 8. Changes in micro structures for 390°F. aging from extruded condition A, B, and C are longitudinal sections aged 0, ½ and 3½ hrs. D is perpendicular section aged 3½ hrs. 100X

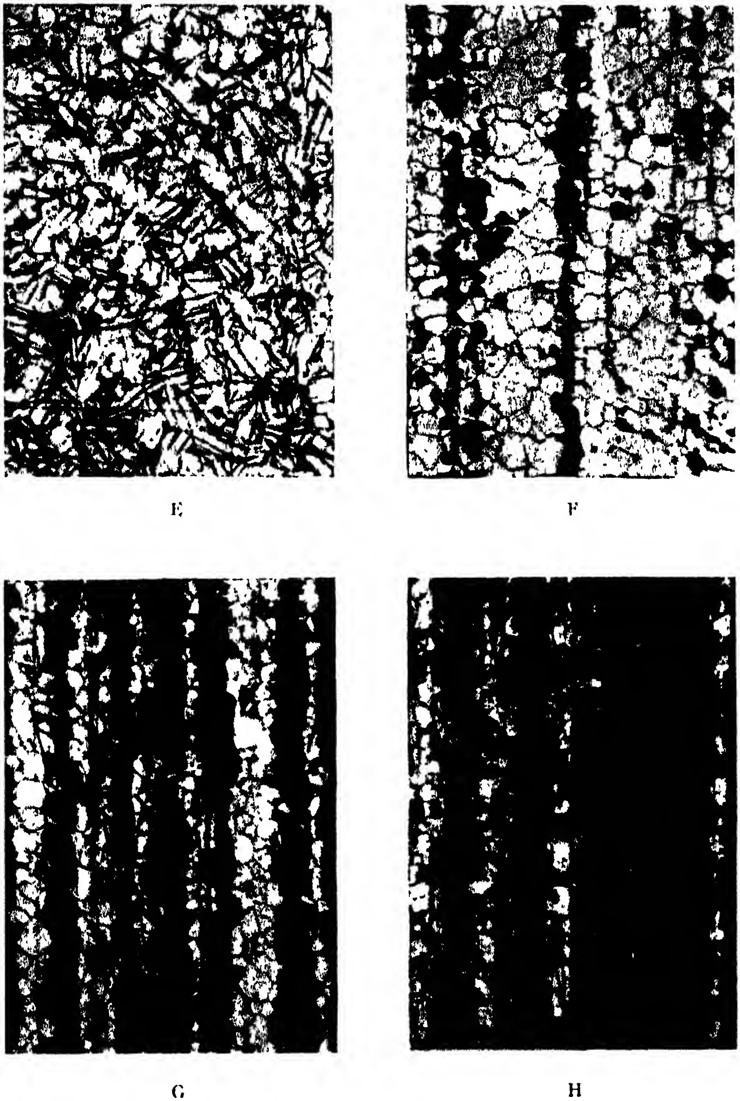


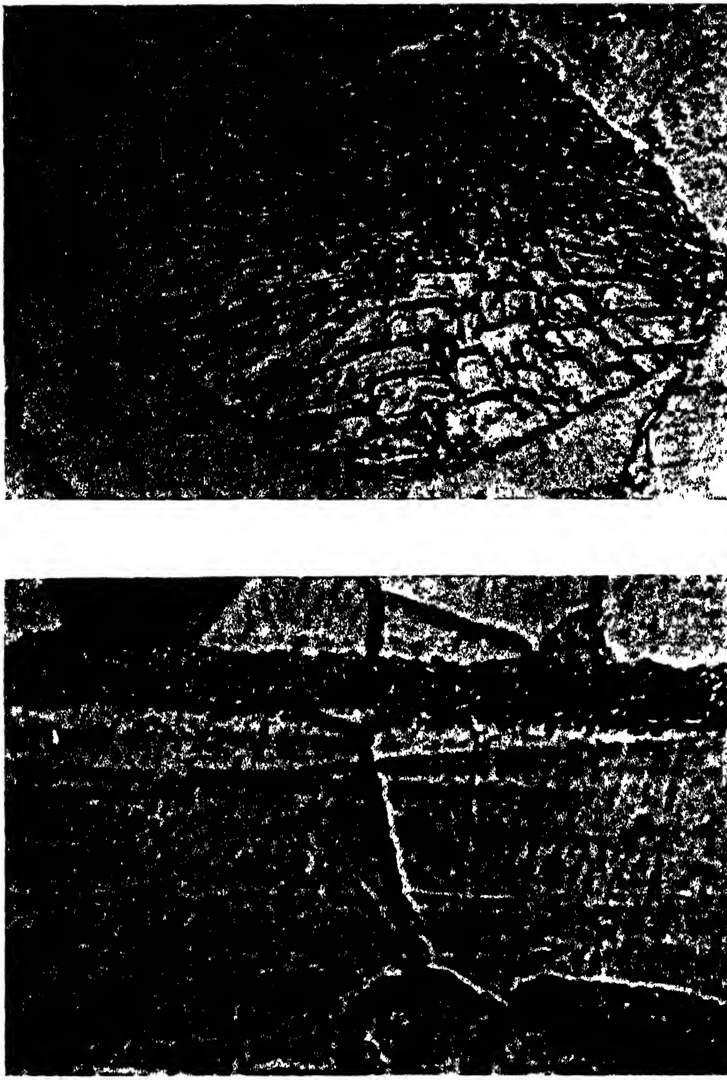
Fig. 8 Changes in micro structures for 390°F aging from extruded condition. E is a perpendicular section aged 3½ hrs. F, G and H are longitudinal sections aged 10½, 16½ and 61 hrs. respectively. 100X.

before the inner section and show the annealing twins first. The twinning at the outer edge is the opposite of the condition obtained when aging from the annealed condition. This is explainable as in the latter case the outside was more completely annealed than the inside during the 775°F. annealing treatment. That this twinning should be evident on the perpendicular sections and not on the longitudinal sections is also, as has been previously discussed, due to the preferred orientation of the crystals resulting from the extrusion process.

The increase in hardness and strength with continued aging is explained by Figs. 8F, 8G and 8H which show an increase in the amount of the precipitated areas. The precipitation is seen to follow the original extrusion axis. These areas start at the grain boundaries and in many cases completely surround a grain. The actual structure of these areas is best seen by referring to Figs. 9 and 10.

Figs. 9A and 9B are micro-structures taken at 2000 diameters of a specimen aged 27 hours and 10½ hours respectively at 390°F. Fig 9A shows the actual formation of the structure within a grain. The intermetallic compound Mg_3Al_2 precipitates out in layers and very closely resembles pearlite, the eutectoid of steel, in its appearance This represents a grain that either had a higher aluminum concentration than the adjoining ones, or was more severely strained, thereby producing a higher degree of super saturation. It could also be that the section so shown was cut so that it was near the grain boundary where the precipitation starts. Fig 9B shows precipitation along an extrusion stringer and also along a grain boundary. It should also be noticed that there is some visible precipitation throughout all the grains, but these differ somewhat from corresponding sections studied from specimens aged from the annealed state. In the case of the latter there is a more general precipitation throughout the grains which resembles a sorbitic structure which could account for the greater strength attained by the material aged from the annealed state. This was illustrated in Fig. 5G.

Fig. 10 shows a larger section and includes a typical precipitated area, precipitation around a grain boundary, precipitation within a grain and an inclusion. Since all other views have shown precipitation to start at grain boundaries, it is quite probable that what appears to be a precipitated area starting within the grain, really started at the



B

Fig 9. Formation of precipitated structures. Specimens A and B have been held at 390° F. for 27 and 10½ hrs respectively 2000X

Fig. 10 Structure showing an inclusion and precipitated areas. Specimen aged 27 hrs. at 390°F. X2000

boundary and grew in sort of a core-like structure. This grain with the core-like precipitated volume when cut through would present an appearance as seen in Fig. 10. The inclusion represented in this figure was commonly observed and when viewed under the microscope presents a blue appearance. These inclusions upon test showed a sulphur reaction.

AGING FROM A PARTIALLY ANNEALED CONDITION

Fig. 11 and Table III give the changes in the physical properties accompanying the 390°F aging of specimens that were previously annealed one and one-quarter hours at 800°F. The aging under these conditions is very similar to the aging from a more fully annealed condition as previously described.

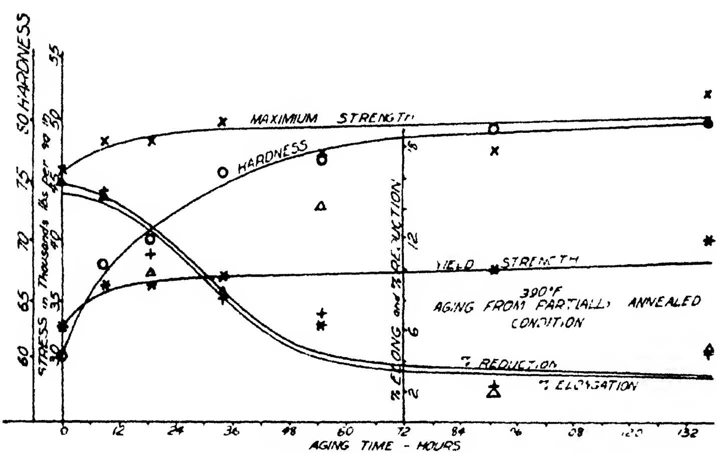


Fig. 11 Physical properties accompanying aging at 390°F following 1¼ hrs anneal at 800°F

TABLE III

390°F Aging Following 1¼ Hrs at 800°F															
No.	Time	Initial Hardness	Final Hardness	% Elong.	% Red.	% Unit Elong.	.1% Yield	.2% Yield	Johnson's Yield	Stress at .7% Yield	Stress at .75% Yield	Stress at .8% Yield	Maximum Strength	Stress on Orig. Area at Failure	Stress on Final Area at Failure
230	0	60.2	76	15	15.8	18.7	31850	32750	29750	31150	31750	32100	45400	45400	53900
231	9½	67.8	78.9	15	14.8	17.8	33350	36200	33500	34000	34850	35400	48500	47700	58000
232	18½	70	77.3	11	9.7	11.25	36350	38250	32750	32500	34250	34750	48400	48400	53800
233	34	75.4	81.7	8	8.7	9.5	35250	36750	31750	34350	35100	35800	49800	49800	54600
234	56	76.8	79	7	14.2	16.5	31250	35000	29750	37700	38100	38350	47000	47000	54750
235	91½	78.9	79.7	2	1.9	2	36250	37250	35000	35000	36000	36750	47300	47300	47400
236	139	79.5	82	4.5	4.6	5	38000	40000	34250	37500	38500	39250	53900	53900	56600

RELATION BETWEEN CHARACTERISTIC STRENGTHS AND YIELD VALUES

Using the maximum strength as unity Table IV gives, for the various aging conditions, the other characteristic strengths expressed as a percentage of the maximum strength The values for the various yield strengths are higher than those previously reported from the study of annealing characteristics as reported in the previous bulletin of this series[8]

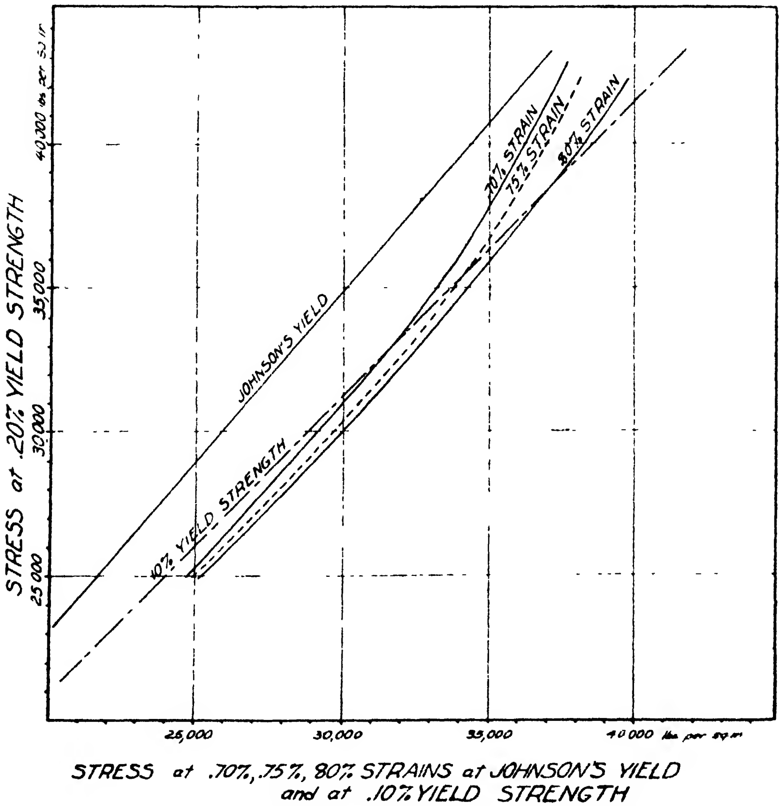


Fig 12 Correlation between characteristic yield values

Fig 12 gives a correlation between the stress corresponding to 20% yield strength and the other characteristic yield values The range of values used for obtaining these curves includes those obtained

from the previous study of the annealing characteristics, together with those obtained from this study As would be expected, the relation between the .20% yield strength and the .10% yield strength is linear The relation between Johnson's Limit is also linear but the relation between the stresses corresponding to strains of 70%, .75%, and 80% are not linear By use of these curves it is possible to obtain values for the 20% yield strength indirectly by taking the stress corresponding to that of a specified set thereby eliminating all the work necessary for taking stress strain readings and plotting the stress strain diagrams An examination of Fig 12 tells considerable about the character of the stress strain diagram corresponding to the various .20% yield strengths The shape of the stress strain diagram can be visualized by using the relations between the values given.

TABLE IV

Temp	.10% Str	20% Str	Johnson's Limit	70% Str at	75% Str at	80% Str at	Max Strength	Break Str	True Break Stress
300° F	74.6	78.03	66.86	71.15	73.44	75.56	100	100	105.93
390° F	70.4	73.6	65.7	70.8	72.6	73.7	100	99.8	110.9
300° F.	71.5	74.3	64.8	70.16	71.69	72.9	100	98.65	116.15
420° F	68.2	70.9	59.0	70.1	71.0	71.8	100	99.3	112.9
420° F	68.17	71.4	60.7	69.0	71.0	72.1	100	99.8	106.3
370° F.	73.7	76.6	66.4	70.8	72.6	74.6	100	99.05	105.1
390° F	70.1	72.8	64.1	69.4	71.8	72.1	100	98.7	114.2

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The Development of a Domestic Stoker to Burn Washington Coals

by Frank W. Candee

Assistant Professor of Mechanical Engineering

ENGINEERING BULLETIN NO. 56

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

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The Development of a Domestic Stoker to Burn Washington Coals

F. W. Candee

The modern domestic coal stoker with automatic control has proved itself a remarkable contribution to home comfort health and convenience, and its rapid adoption has been well deserved. With "Comfort in the Home" well established it is only natural that the furnace operator become interested in cheaper fuel and more efficient heating equipment. Many makers have been attracted to the field and their stokers have attained a good standard of effectiveness and efficiency. So far, however, they have burned with least difficulty a narrow range of types of free burning, non caking fuels that are not everywhere available at a satisfactory price. Attention was directed to this point by one of the leading coal companies[1] of the State of Washington by a request that studies be made of this problem, and some type of retort or stoker be developed that would make possible the burning of their fuel in direct competition with stoker coals already on the market. This is an important problem for the Engineering Experiment Station for the reason that every effort is being made to promote further development of the natural resources of our state.

The advantage of the stoker over hand firing for domestic heating has been well established, and so will not be discussed in this report. All grades of slack or stoker coal cannot be burned successfully in the stokers as they now exist on the market, bearing in mind that what the home operator desires is a piece of equipment that requires the minimum of attention on his part and but a yearly inspection by the service man.

The following analyses show how this coal in question compares with a satisfactory stoker coal now on the market.[2]

Heating Value

B. T. U. per pound (as fired)

[1]Washington Coal (washed)	12,600
[3]Utah Coal	12,590

[1] The Roslyn Cascade Coal Company

[2] Bulletins No. 27 and 39, Engineering Experiment Station, State College of Washington, and elsewhere

[3] Utah Castle Gate, Helper, Utah

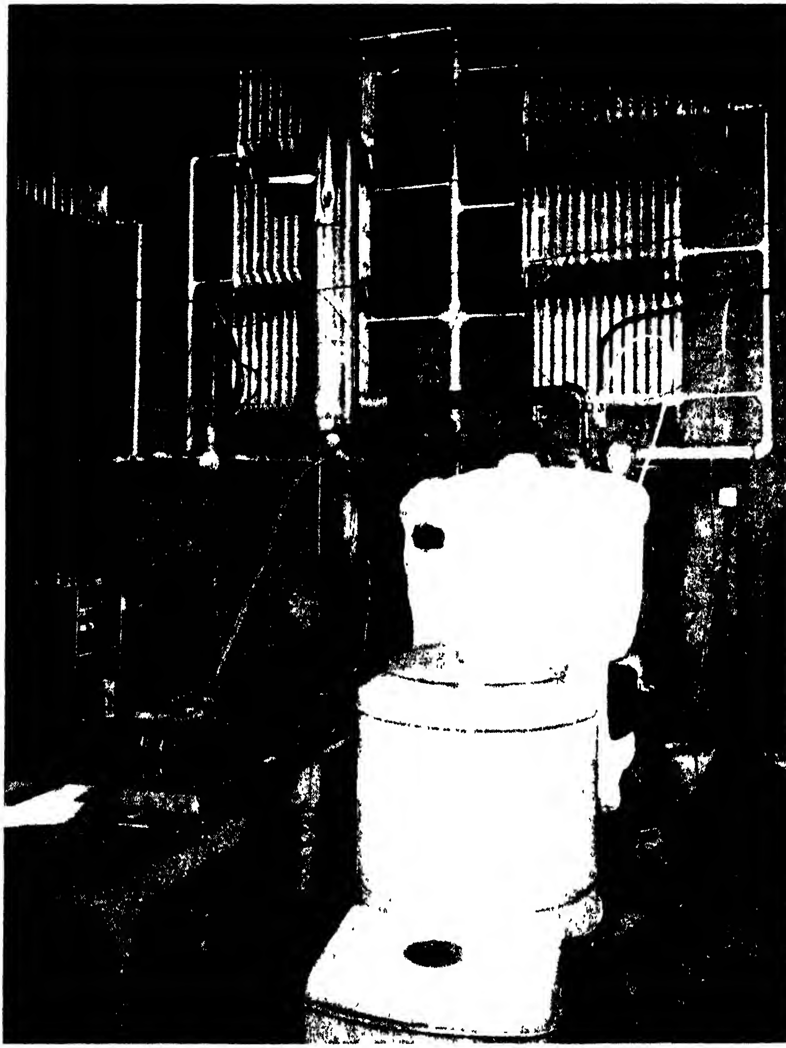

Fig. 1 Arrangement of equipment for running coal tests

Approximate Analysis (as fired)

	Washington Coal	Utah Coal
Volatile	35.77%	38.01%
Fixed Carbon	53.38%	52.22%
Moisture	1.73%	2.35%
Ash	9.14%[4]	7.42%
	100.00%	100.00%

Ultimate Analysis[5] (as fired)

	Washington Coal	Utah Coal
Carbon	74.20%	75.06%
Hydrogen	4.78%	4.87%
Nitrogen	1.44%	1.44%
Oxygen	8.73%	8.86%
Moisture	1.73%	2.35%
Ash	9.12%	7.42%
	100.00%	100.00%

In comparing the analyses of the washed Washington coal and the Utah coal there would not appear to be enough difference, outside of the moisture and ash, to make one coal better suited for stoker firing than the other. The Utah coal is classed as "free burning" while the Washington coal is a "coking coal."[6] This would not constitute a difficulty if it were not for the fact that this coke also "cakes," and in order to burn this mat or cake, a blasting draft is required. This causes blow holes and consequently a large excess of air, and results in low furnace efficiencies. When this coke is mechanically broken up by poking, a very efficient fire results, but the home operator would refuse to burn a coal that called for frequent attention.

To aggravate this condition, the ash has a very high fusion temperature—around 2700 degrees F., and so the clinker that forms is a porous, partially fused mass that quickly fills up the fire box and shoves the coke out of the burning zone. How to prevent the formation of this "cake" and devise some methods for automatic removal of clinker or ash became the major problem.

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[4] Washing reduces ash content from about 14% to value shown.

[5] By formulae.

[6] Marks Handbook, Second Edition, 1924, Page 632.

Method of Attacking Problem

It was decided that a heating plant similar to the average domestic hot-water heater system should be installed and efficiencies determined while operating on the "on and off" basis as it would actually perform in the home, rather than to base tests on steady operation as carried on in a power or central heating plant

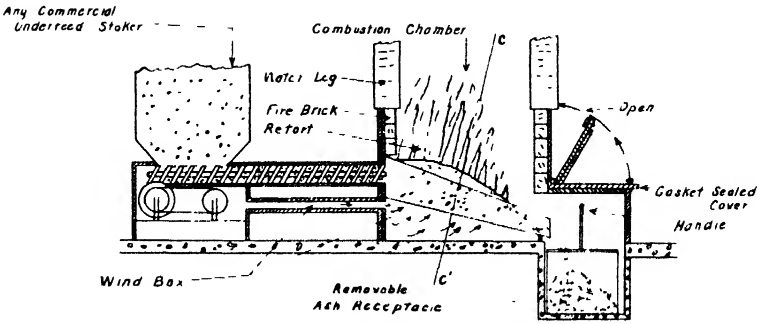


Fig 2 Arrangement of tuyere for burning of high ash caking coal

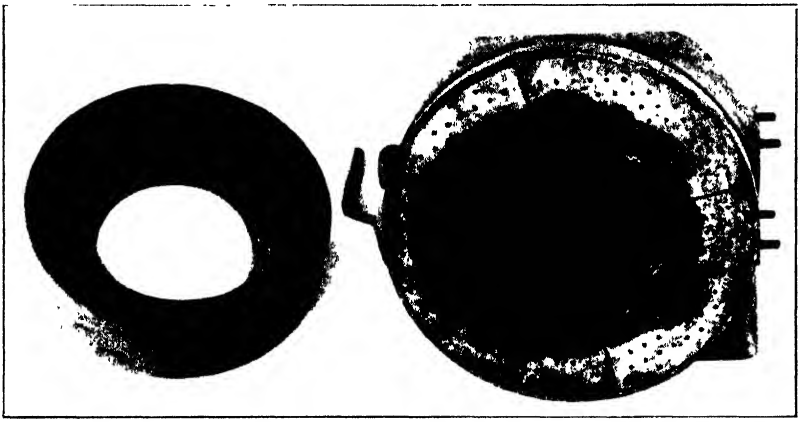
The set-up of equipment to carry on tests with this Washington coal is illustrated in Fig. 1, and Fig 2 is a drawing of the general arrangement with the type of tuyere finally adopted The hot-water furnace and radiators used are the type found in the average home By placing the radiators at different levels the ordinary gravity system with expansion tank was duplicated In order to operate this experimental plant in the summer, as well as in the winter, provision was made for running water over the radiators, thus dissipating the heat With this system the on-and-off periods could be regulated at will.

To determine the overall efficiency and compute the heat balance, thermometers, thermocouples, CO_2 meters and a water flow meter were installed This flowmeter[7] (A) Fig 1, which is easily calibrated at any time during a test, measures the very low velocities encountered in hot water systems of the gravity type, and at the same time does not interfere with the normal gravity flow in the system

[7] Described in Bulletin No 39, Engineering Experiment Station, State College of Washington

An "aquastat", (B) Fig 1 with a mercoid switch, stops and starts the stoker when the circulating water reaches desired maximum and minimum temperatures

The stoker[8] selected was of recognized performance and one commonly found in homes This stoker was equipped with a retort similar to those found on all other makes on the market and illustrated by (A), Fig 3 In addition to this retort, the stoker company sent one specially designed to burn a caking coal This retort is shown in (B), Fig 3



A B

Fig 3 Types of tuyeres used on domestic stokers

This stoker has a variable speed arrangement for coal feed,—13, 24, and 35 pounds per hour—and after preliminary tests had been made to determine which feed would give the best burning condition for our size of furnace, the intermediate rate was chosen The lowest speed produced an excess of fly ash and very little clinker, and the highest speed built up an excess of coke that could not be made to burn out without frequent removal of clinker that formed with the deep fuel bed If this clinker was not removed it would shove the coke out of the burning zone and finally completely fill the fire box with unburned combustible and clinkers

[8] Iron Fireman.

The pin-hole tuyere block (B) Fig 3 was installed for the tests, as previous tests indicated that the standard tuyere could not burn the coking coal successfully and still maintain the full automatic features expected of the stoker method of firing

Several preliminary tests were run to determine, if possible, the air setting that would give the best combustion as indicated by analysis of the flue gas A definite value was given to this air setting to indicate whether the amount of air was being increased or decreased between runs It was also noted that as the CO_2 reading increased, the stack temperature approached 1000°F This was due to several features of design embodied in the conventional hot water heating unit. Briefly, these are lack of sufficient volume for complete combustion, presence of relatively cold surfaces in the combustion chamber, and a lack of sufficient heat transfer surface in the heater for the rate of firing used[1] An efficiency of 60% could not be exceeded due to the heater design so this cannot be attributed to the stoker, the element upon which experimental work was being done

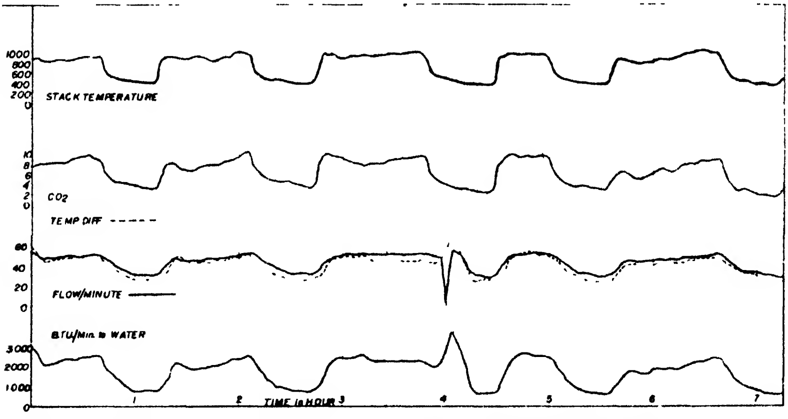


Fig. 4 Typical plot of results for calculation of efficiency and heat balance

Fig 4 is an illustrative plot of results used to calculate the efficiency and heat balance of each run.

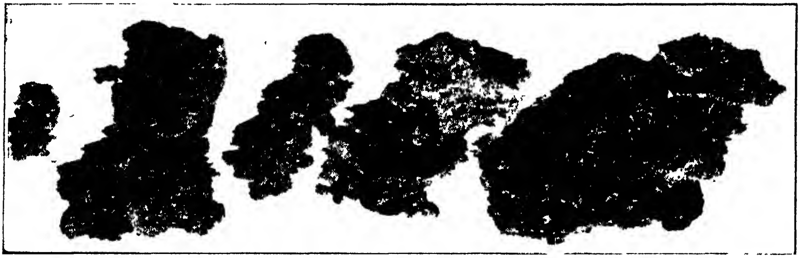
Table 1 is a summary of nine representative tests run under various conditions as to type of tuyere, air setting, and refractory

[1] Discussed at some length in Engineering Experiment Station Bulletin No 39

TABLE I

Test No	Type Tuyere	Air Setting	Length of Test	Coal: Kind	Coal: Amt Used (lbs)	Clinker*: Amt Formed (lbs)	Clinker*: Texture	% of Coal Fired	Eff %	Rate Feed Coal	Remarks
1	pin hole	1.2	4 hr	R C S (W)	30.25	½	Poorly fused	1.7	52.9	13.5 lbs per hr	Excessive fly ash
2	pin hole	1.8	7 hr 9 min	R C S (W)	112	11.5	Porous bulky	10.5	55.8	26 lbs per hr	Clinker porous and bulky
3	pin hole	1.8	6 hr 13 min	C G U (O)	97.5	4.5	Glassy non-porous	4.62	56.3	26.35 lbs per hr	Clinker glassy and non-porous
4	pin hole	1.43	4 hr 15 min & 24 hr	C G U (O)	57.75 & 361.75	2 & 14	Glassy non-porous	3.47 3.86	65	23.4 lbs per hr	High per cent of fly ash
5	pin hole	1.43	4 hr 18 min & 24 hr	R C S (W)	57 & 382	3½ & 32½	Porous bulky	5.71 8.45	57.8	25 lbs per hr	Deep fire fused more ash
6	pin hole	1.6	4 hr 3 min & 24 hr	R C S (W)	55 & 380	1½ & 28½	Porous bulky	2.73 7.8	60.4	24.3 lbs per hr	Clinker fused better than Test 2
7	standard tuyere	2	4 hr 2 min & 24 hr	R C S (W)	60 & 375	5½ & 32½	Porous but less bulky	8.75 8.7	49.2	24.3 lbs per hr	Smoky fire Little fly ash
8	standard tuyere (refractory & cast iron block)	1.8	7 hr 15 min	R C S (W)	100	8½	Better fused; bulk reduced	8.5	55.1	24 lbs per hr	Pin sheared at end of 12 hours
9	Same as No 8	1.4	2 hr	R C S (W)			Non-porous				Tuyeres blocked Tests stopped before pin sheared

R C S (W) — Roslyn Cascade Slack (Washed)   C G U (O) — Castle Gate Utah (Oiled)   * Fused ash only



1 2 3 4 5

Fig 5 Clinker removed from furnace at end of tests 1, 2, 3, 4, and

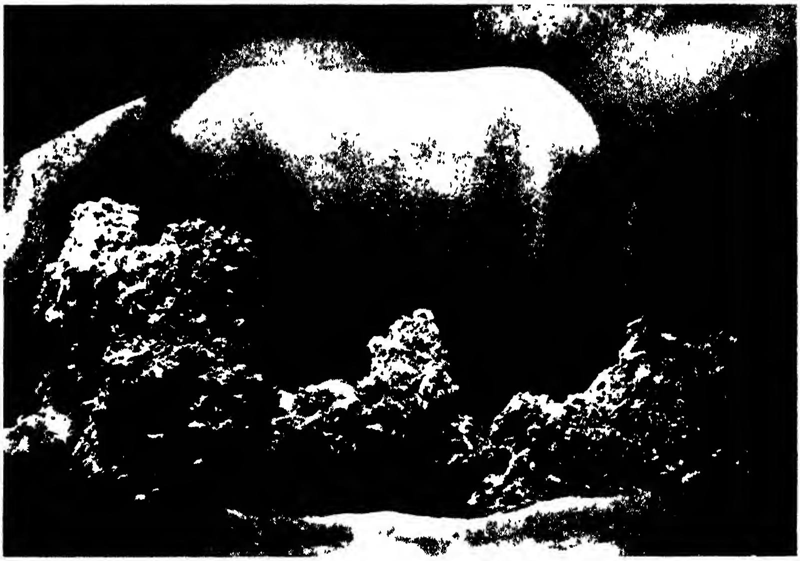


Fig 6 Accumulation of clinker in furnace at end of 24 hour run with standard tuyere

surfaces in the furnace Fig 5 shows the clinker obtained from the tests indicated by the numbers 1, 2 and 5 are from the Roslyn Cascade Slack coal while 3 and 4 are from similar runs with the Castle Gate Utah Fig 6 shows the clinker as it built up in the furnace with no attendance for twenty hours.

A study of these results and other observations, gave rise to the conclusion that some other form of retort would be required to burn this high ash, caking coal in the domestic stoker.

Efficiencies of over 80% had been obtained with the Roslyn-Cascade coal in the college heating plant using the multiple retort underfeed principle of burning. With this in mind a retort that would permit the continuous travel of coal through the furnace with an ash discharge at the rear was designed. The first experimental re-

A B

Fig. 7. Experimental retorts designed for continuous discharge into ash receptacle.

tort (A) Fig. 7 was fabricated out of steel plate so as to make a study of proportions, slope angle, and rate of feed. The results obtained with this retort indicated that the coal could be burned in this manner and the ash successfully discharged. Patterns were worked out for a cast iron retort with tuyere blocks as shown in (B) Fig. 7. Table No. 2 gives a summary of tests made with this retort. Many difficulties were encountered in the form of fusion of the clinker to the refractory surface, the warping of the tuyere blocks and the discharge of the large coke trees into the ash pit. If the fuel bed was disturbed during the runs the amount of combustible in the refuse was greatly reduced. Without this agitation of the fire, burning took place around the outside edges only, as air could

not be forced through the coke mass in the center. Various devices were placed in the rear of the retort to hold this coke until it was burned, but this also stopped the proper discharge of the clinker. If the fire was left unattended for twelve or more hours, the discharge to the ash pit would cease entirely and the same conditions would exist in the fire box as were pointed out with the standard retort; namely the accumulation of bulky clinker and coke shoved up out of the burning zone.

From this series of tests it was determined that some form of breaker or agitator must be introduced into the set-up before good efficiencies and elimination of combustible in the refuse could be realized. Moving grate bars would complicate and increase the cost of retort, so the idea of placing some obstruction in the path of the coal travel was tried.

Figure 8 shows the shapes placed in various positions in the path of the coal feed. Repeated tests with these obstructions failed to find a successful arrangement. A compact clinker shaped like the

Fig. 8. Various shapes placed in retort to agitate coal and prevent formation of coke trees.

lower part of the retort would shove into the ash pit and unless someone was there to attend it every few hours the discharge would stop, due to the clinker resting on ash container, and fusion of clinker to the refractory would begin. Figure 9 illustrates clearly this clinker problem. In breaking off this clinker, pieces of refractory would spall away and soon the furnace would have to be shut down for repairs.

Various devices for the intermittent breaking up of the fuel bed were studied, but none seemed applicable to our problem for it was observed that it took a blow to break the coke trees that formed, especially if the coal had an excess of fines[11] It was decided that if

Fig 9 Clinker discharge that causes stoppage and fusion to refractory

the coke breaker were to be moved back and forth through the fire that it would break up the coke during its formation and at the same time discharge the ash before a high degree of fusion would take place An auxiliary drive was set up that had a variable speed adjustment of from two or five agitations per minute One form of agitator used successfully is shown in Figs. 8 and 11, the drive causing the agitator to slide back and forth along the tuyere With this equipment it was found that the higher speed did not break up

[11] Roslyn Cascade stoker coal after passing through the washing and drying plant averaged 50% passing the 1/4" mesh screen

Fig. 10. Cam wheel, for moving agitator, attached directly to auger drive

the coke as well as the lower speed and also it discharged so rapidly that the lower end of the retort became bare and increased the excess air to a point where it materially reduced the efficiency.

The majority of domestic stokers on the market turn the coal auger at approximately one revolution per minute so the auger can be used to drive the agitator through gears or cams. Figure 10 shows such a set-up with the cam wheel attached directly to the auger and

acting through the shear pin so that the protection against stoppage is not impaired. The side tuyere blocks were removed for they were subject to severe warping. A lining of high grade refractory was provided to replace these blocks, reducing the metal parts exposed to high temperatures to the main retort and agitator as shown in Fig. 11. The tuyere holes were increased in both the base and breaker so that a blasting effect would force the air up through any break that would be made in the coke, and burning would take place throughout the cross-section instead of around the edges. It was now found possible to secure uniformly satisfactory conditions for efficient combustion.

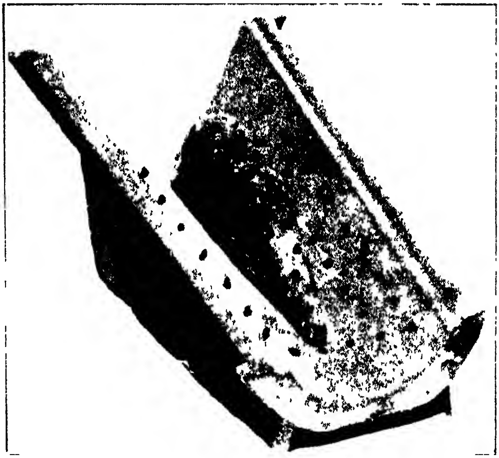


Fig. 11. Retort and moving agitator ready to be attached to an underfeed domestic stoker.

This last set-up was put on test, but before an actual efficiency run was made the fire had been burning for a week in order to make observations as to the best air setting that would give a minimum of combustible in the refuse. No trouble with fusion to the refractory or failure of a regular ash discharge occurred during this time. A three hour efficiency run (No. 15) was made, but due to an excess only forty-eight percent was realized. Combustible in the refuse was 24% of the refuse. The air setting was gradually reduced until the CO_2, during the preliminary running period, was 12% or better.

TABLE II

Test No.	Type Tuyere	Air Setting	Length of Test	Coal Kind	Coal Amt Used (lbs.)	Clinker Amt Formed (lbs.)	Clinker Texture	% of Coal Fired	Eff %	Rate Coal Feed lb/hr.	Remarks
1	C I	1.8	4 hr	R C S (W)	63.5	9.5	Porous bulky	14.95	26.6	24	25% combustible in refuse Blow holes in fire
2	C I	1	1 hr 30 min	R C S (W)	20	4	Small Clinkers	20	Not calcu-lated	13	30% combustible in refuse 150% excess air
3	$C I_1$	2.2	3 hr	R C S (W)	70	11	Porous Bulky	15.7	33.2	24	Changed air distribution during test by baffle
4	$C I_1$	2.5	3 hr	R C S (W)	43	6	*Continuous Clinker	13.9	48	24	Agitator No 4 8.4% Combustible
5	$C I_1$	2.2	3 hr	Rock Springs	47.5	3.5	Small Clinker	7.36	39	24	Agitator No 4 41% Combustible in refuse
6	$C I_1$	4	2 hr 45 min	R C S (W) (O)	41.5	5.5	Poorly Fused	13.2	50	24	Agitator placed at toe of retort 30% Combustible
7	$C I_1$	3.4	3 hr 30 min	R C S (W) (O)	50	6.5	Long Clinker	13.0	58.8	24	Agitator placed at center of retort
9	$C I_1$	3.4	2 hr 30 min	R C S (W) (O)	27	3	Long Clinker	11.4	62	24	Tuyere area increased at end of retort 7% Combust
10	$C I_1$	3.4	3 hrs	R C S (W) (O)	61	6	Long Clinker	9.85	56.5	24	Coal screened all below ¼" out. Blow holes in fire

TABLE II (Continued)

Test No	Type Tuyere	Air Setting	Length of Test	Coal Kind	Coal Amt Used (lbs)	Clinker Amt Formed (lbs)	Clinker Texture	% of Coal Fired	Eff %	Rate Coal Feed	Remarks
11	C I$_1$	3.4	6 hr	R C S (W) (O)	87	8	Long Clinker	9.43	57	24	Conducted by class in Steam Laboratory
14	C I$_2$	3.4	6 hr 15 min	R C S (W) (O)	127	14	Small Clinkers	11.02	48	24	Strokes of agita two min 3.5% combustible in refuse
15	C I$_3$	2.6	2 hr 52 min	R C S (W) (O)	38	4.5	Refuse in Granular form	11.8	49	24	Fusion to side walls 2.5% Combustible
16	C I$_3$	2.3	3 hr	R C S (W) (O)	44½	5	Refuse in Granular form	11.21	46	24	Blow holes in fire Burning of agitator 3% Combustible
17	C I$_3$	2.0	2 hr 45 min	R C S (W) (O)	37½	4	Small compact clinker	10.61	55.7	24	No fusion to walls 3.5% Combustible

R C S—Roslyn Cascade Slack (W) Washed (O)—Oiled

C I —Cast iron retort with tuyere blocks—No agitator

C I$_1$—Cast iron retort with tuyere blocks Stationary agitator

C I$_2$—Cast iron retort with tuyere blocks—Moving agitator (experimental drive)

C I$_3$—Cast iron retort without tuyere blocks—Moving agitator (stoker driven)

*—See Fig 9

†—Test 8 Experimenting with blunt agitator, not satisfactory

‡—Test 12 & 13 Experimenting to determine the best number of strokes per min for agitator

Another three hour test (No 16) was then made and only 46% efficiency resulted The amount of combustible in the refuse was 3%. This lower efficiency was caused apparently by blow holes that developed in the fuel bed

Throughout all these tests it was observed that the coke had a tendency to bridge over the retort and form an arch of coke that would not be effected by either the stationary or moving agitator This also increased the tendency for fusion of ash to take place on the refractory walls By using a high grade moulded refractory for a lining this fused clinker could be broken off without injury Nevertheless, this clinker would build up trouble for the householder unless it was looked after each day Before running Test No 17, the retort was removed from the furnace and inspected for burning The side walls showed no evidence of excess heating, but the agitator was burned on the top It was apparent that the whole retort was too narrow and that the agitator was too high on the leading edge A new shape was devised for the agitator with the cross-section and height reduced, and also a step in the top surface to help to break away pieces of coke on the return stroke as well as the forward stroke The tuyere area was increased in the back of the agitator but decreased in the retort proper so that the rapid burning of the coke is completed in a short travel along the retort without the development of blow holes The coke that is now present in the refuse is due to pieces rolling in as a clinker breaks and falls into the ash receptacle This can be corrected by leveling off the end of the retort

Test No 17 of Table II shows an efficiency of 55.7% Tests 7, 9, 10 and 11 show efficiencies in excess of this amount, but in these tests the problem of discharge was unsatisfactory After the completion of Test 17, the stoker continued to run for two weeks under the same conditions and no difficulty was encountered in discharge, fusion of ash, burning of metal parts, or increase in the amount of combustible in the refuse, no poking or cleaning being required

Satisfied that the Roslyn Cascade Slack could be burned successfully at the rate of twenty-four pounds per hour, runs were made at the lowest feed (13 lb/hr) and the highest (35 lb/hr) In each case the ash was free from combustible matter but the efficiencies dropped

to around forty five per cent In the first case the fire was not thick enough to prevent blow holes from forming, although the draft under the fire was greatly reduced The fire was too small for the size of the tuyere In the second case, the opposite was true in that a very long flame developed and continued to burn even out into the breeching, so that the stack temperatures ran well over 1000° F Also, a loss resulted from an increase in unburned gases

Utah Castlegate coal was next burned at 24 lb hr rate, and an efficiency of sixty five per cent was obtained, but due to the lower melting point of the ash, the agitator became coated with it during the down period and then burning of the metal took place during the on periods This same thing happened when Rock Springs coal was burned, with the exception that the loss due to unburned hydrocarbons exceeded that of any other coal used The surprising part of the last run was that the Rock Springs coal needed as much agitation as the Roslyn Cascade to prevent combustible appearing in the ash, while the Utah coal needed only half as much

Summary and Conclusion

This report deals directly with the various experimental retorts set up in an effort to successfully burn Roslyn-Cascade slack coal Due to the inefficient type of hot-water boiler used, excessive losses to the breeching and stack cannot be avoided, this loss in the majority of tests with domestic boilers of this type amounting to 30% or better[1]

The automatic removal of the ash from the furnace, and prevention of loss of combustible matter in the ash was the desired goal, with efficiency being used as an measure of progress

Due to the caking properties of this coal a high draft pressure is required to burn it on any stationary grate and so excess air, due to blow holes, is hard to prevent both during the running and down period This excess air carries heat up the stack, resulting in the above mentioned losses

The moving agitator breaks up the coke as it forms and allows the air to come in contact with all sides of it The air pressure can

[1] Report of Investigations R I 3370 Bureau of Mines, University of Washington, Seattle, Washington Engineering Bulletin No 30, State College of Washington, Pullman, Washington

then be reduced and an increased efficiency results. If the agitation is not too violent, the smaller pieces of coke will nest together and prevent blow holes from forming. The air pressure can then be regulated to give the best possible efficiency with high CO_2 and the minimum combustible appearing in the ash.

With this coal burned in the common type of tuyere used in domestic stokers, it has been found to be impossible to consume all the coke and keep the efficiency up without requiring more attention than the householder would be willing to give. But with the new retort satisfactory efficiency is attained, the combustible in the refuse is reduced to 3% and less, and a perfect discharge takes place without any attention other than changing the ash receptacles

To assure long life to the agitator it should be coated with a plastic refractory or be made of a special heat resistant cast iron.

Acknowledgement

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A Two Way Photo-Electric Traffic Counter

By Homer J. Dana

Assistant Director Engineering Experiment Station

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

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A Two Way Photo-Electric Traffic Counter

With Notes on the Selective Type of Counter

By Homer J. Dana

Assistant Director, Engineering Experiment Station

INTRODUCTION

During recent years traffic counts on various parts of our highway systems have become increasingly desirable and important, and furthermore, are being required where Federal funds[1] are to be allocated. In 1935, because there was no satisfactory automatic recording two-way traffic counter commercially available, the State College of Washington, in cooperation with the Washington State Highway Department,[2] undertook the experimental development of such a counter. During 1936, an automatic graphic recording two-way traffic counter was designed and built and for the past fourteen months has been subjected to tests in actual use on the State highway system.

When construction of this counter was undertaken, it was found that there was available almost no information at all on the application of photo-electric cells which could be read and understood by any but the most technically minded person. With photo electric counters coming into more general use, information is still lacking with which the average highway official can acquaint himself with the principles of the traffic counting equipment he must use.

Therefore, this report is written, not only to describe the automatic graphic recording two-way traffic counter developed at the State College of Washington, but also to set forth a description of the fundamental principles of any traffic counter using the photo-electric cell to actuate a counting mechanism.

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[1] Public Roads, May 1938.

[2] Appreciation is expressed to Lacey V. Murrow, Director of The Washington State Highway Department, for cooperation in developing and testing this traffic counter.

Also to Mr. W. A. Stancer, Assistant Traffic Engineer under Mr. C. E. Fritts of the State Highway Department, who gave valuable assistance and helpful suggestions in the preparation of this manuscript.

To Marshall Arlin, student in the College of Engineering belongs considerable credit for development of the electrical circuit of the counter.

PRINCIPLE OF THE PHOTO-ELECTRIC CELL USED FOR COUNTING

The photo-electric cell has been used for several years in the counting of people, or the counting of packages or units in a factory. Rays from a lamp on one side of a passage way or a conveyr are directed into a light-sensitive cell on the other side, allowing current to flow through the circuit connected to this cell. When the light is interrupted, the current ceases to flow. Although this current is extremely small, being in the order usually of one to twenty micro amperes, and too small to operate a power relay, yet it is adequate to control a vacuum tube amplifier, which in turn will control relays, switches, counters, etc.

The photo-electric cell usually selected for use in a traffic counter employs an active surface of caesium deposited on oxidized silver. The tube is filled with argon gas to produce ionization and thus further the electron emission. When light falls on the caesium cathode of such a tube electrons are released and pass over to the anode, thus causing a flow of current through the associated circuits. The gas-filled tube is not quite so stable as the vacuum type of tube, but its output is considerably greater, making it well suited for use in a traffic counter. The vacuum type of tube is more commonly employed in equipment measuring light intensity, or in precision instruments.

The current caused to flow through a photo-electric cell by the focused light from a 50 CP bulb, 50 feet across the road, will be from one to four micro amperes, according to the characteristics of the circuit. If, for instance, two micro amperes flow through the PE cell and through a resistance R of 10 megohms, the voltage drop through the resistor will be 20 volts. This is available as negative bias on an amplifier tube to reduce the plate current to the desired minimum. Since this part of the counter circuit is sensitive to exceedingly small currents, it is important that leakage resistance be maintained at a high value. Therefore, the circuit from the anode of the PE cell to the grid of the amplifier tube should be very well insulated.

A SIMPLE COUNTER

A device to count people, passing through a doorway, or packages on a conveyor, etc. includes one lamp with lens, one photo-electric cell with lens, an amplifier tube, a magnetic counter mechanism, and

a power supply. Figure 1 illustrates the fundamental circuit of such a counter.

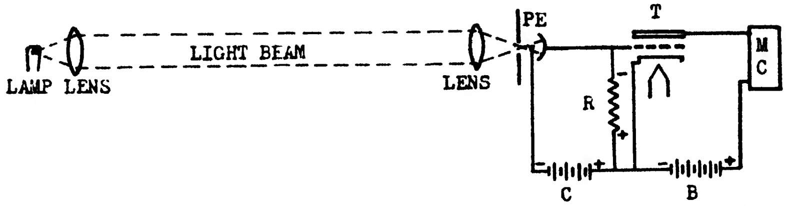

Fig. 1 Fundamental circuit of a counter employing a light beam and a photo-electric cell to control an amplifier tube which operates a magnetic counter.

As long as the rays from the lamp shine into the PE cell, current from the battery or power source flows through PE, and also through resistance R. The voltage drop IR, through this resistor, is designed

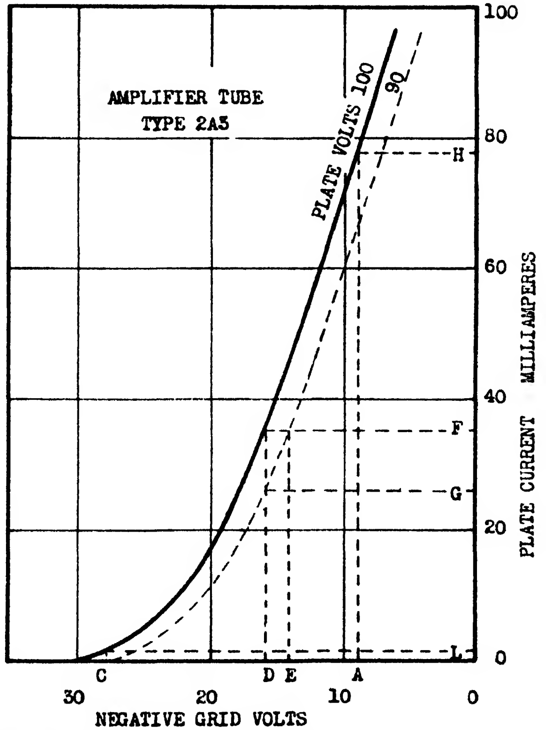

Fig. 2. Characteristic grid voltage-plate current curve of an amplifier tube showing effect of grid control by the photo-electric cell.

to bias the amplifier tube T to, or nearly to, cutoff, except when the light is interrupted to execute a count.

As soon as the light rays are interrupted, (see Fig. 1) the photo-electric cell resistance rises to infinity, thus stopping the flow of current from the battery, with the result that the voltage drop through R becomes zero. This in turn reduces the negative bias on the amplifier tube T from C to A (see Fig. 2), which also causes the plate current to rise from L to H. This increase in current is sufficient to operate the magnetic counter M in Fig. 1.

Upon the restoration of the light beam, current through PE resumes its normal value, biasing tube T nearly to cutoff and thereby reduces plate current to L, which releases the counter magnet, thus completing the count.

It will be noted in this circuit that during the intervals between operations of the counter, the amplifier tube is taking practically no plate current. This type of circuit is usually employed because it assures minimum current consumption and long life of the amplifier tube.

SELECTIVE COUNTER

The counter described and illustrated in Fig. 1 will register each object passing before it, but cannot distinguish as to direction. It will count persons, animals, packages, and vehicles without distinction. If such a counter is equipped with two lights, and two PE cells connected in parallel, (see Fig. 3), then in order to register a count, the object would have to interrup both beams of light at the same time. If these beams are located, say three feet apart, the counter would not register

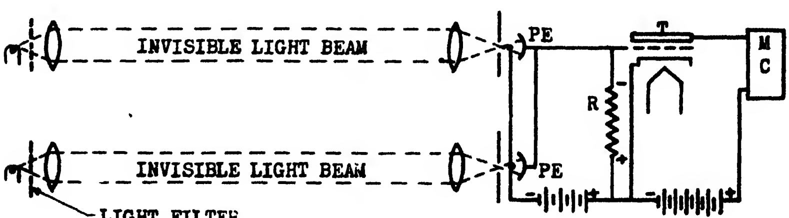

Fig. 3. Two separate light beams operating two photo-electric cells in parallel to control the same amplifier tube. The two beams might also be focused on one photo-electric cell by the use of mirrors, thus eliminating the second photo-electric cell. Note the location of ray filters to make the light beams invisible except to the electric eye.

a single individual, but would count larger objects such as vehicles, etc. This is the principle of the selective counter now available through the International Business Machines Company.

Such a counter totals every vehicle which passes before it without distinction as to direction of travel.

DIRECTIONAL COUNTER

In order to distinguish between traffic going in opposite directions, it is necessary either to separate the traffic into two lanes and count each lane with separate counters, or use a counter which can distinguish direction. A student at M.I.T. originally worked out a system of electrical interlocking relays necessary to accomplish distinction of direction of traffic in the same lane, and the General Electric Company also experimented with such a system for use on a bridge at Cairo, Ill.

The experimental counter developed at the State College of Washington employs mechanically interlocking relays but in addition is equipped with a continuous chart on which is drawn a curve of traffic

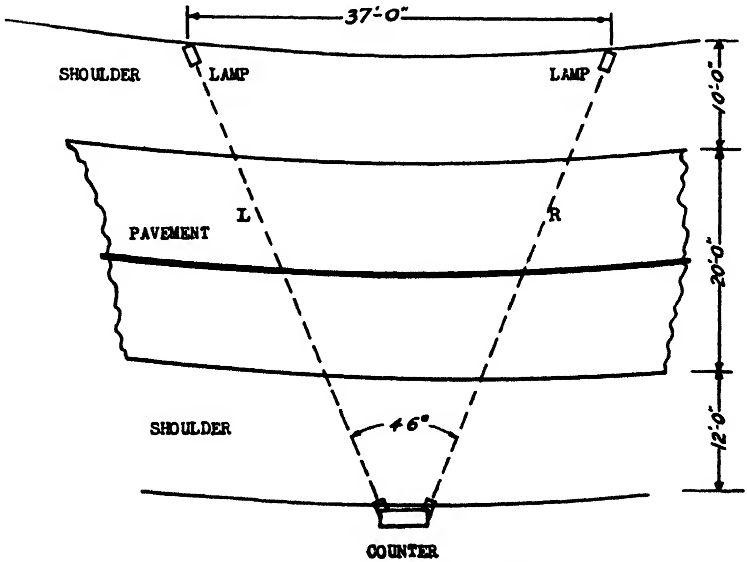

Fig. 4. General layout of traffic counter located on a curve to minimize errors due to cars overtaking and passing each other. This layout is for counting traffic separately in the two directions.

density, and on which also is stamped periodically, and separately, the total traffic in each direction.

PRINCIPLE OF TWO-WAY COUNTER

Briefly, the principle of a two-way traffic counter is as follows: Two separate light beams are directed across the highway to control two PE cells. (See Fig. 4) A vehicle coming from the right will first intercept beam R, which sets up a selective relay in the amplifier circuit. Then when beam L is interrupted it is able through the selective relay already set up, to operate the left-bound counter, which in turn unlocks the selective relay and restores the system to neutral ready for the next vehicle. If the next car is in the same direction, the performance is repeated, but if a car comes from the left, then beam L is interrupted first, and sets up a different selective relay, through which the beam R, when it is interrupted can operate the right-bound counter, etc.

DETAILS OF EXPERIMENTAL COUNTER

In Fig. 5 is shown the W.S.C. counter as installed. The relay mechanism is mounted in a one-eighth inch thick steel case equipped with a storm-tight door. This case is mounted on a four-inch pipe standard, flanged at the bottom and bolted to a concrete pedestal. The two PE cells are mounted in adjustable, lens equipped, compartments attached to the underside of this relay cabinet.

Power is supplied at 110 volts A.C. by wires extending from a roadside pole to the top of a pipe mast on the relay cabinet. No batteries are required. A radio interference filter is connected into the A.C. supply to prevent relay clicks from annoying radio users on the same power system.

The two lamps are located in steel compartments mounted on pipe standards on the other side of the road and are adjustable so that the light beam can be centered directly into the PE cells. Ray filters eliminate all visible rays from the light beams, thus minimizing tampering by the curious. Current to supply the lamps is taken underneath the road in conduit from the relay cabinet where a master switch turns off the power to the system. A step-down transformer at the lamp provides the low voltage for standard headlight bulbs.

The circuit diagram of the relay system is shown in Fig. 6. Only standard telephone and power relays were used throughout, except that the time delay relays were specially built for this work. Some simplification could have been accomplished by building special relays combining the counter relay and the counter magnet.

Fig. 5. Typical layout of lights and photo-electric cells across a highway for counting two-way traffic separately. Concrete pedestals hold the lights in alignment. The light beams are approximately 38″ above the road surface, and are invisible to the motorist or pedestrian. Parallel, instead of diverging beams may be used.

SEQUENCE OF RELAY OPERATIONS

As explained in connection with Fig. 1, the light beam, directed onto the cathode of the PE cell, permits current to flow through the associated circuit which includes resistance R. Referring to Fig. 7, it will be seen that such a current imposes an additional negative bias on the grid of the amplifier tube T. As soon as the light beam is interrupted, the plate of the amplifier tube takes current through the tube relay causing it to close its three pairs of contacts. As yet, only one pair of contacts is active, and that pair energizes the selector relay, enabling a mechanical latch to drop behind the armature to hold it in operated position.

This completes the first part of the counting cycle and the beam may or may not be immediately restored, depending upon the movement of the object which interrupted it.

Fig. 6 Operating and recording mechanism for two-way traffic counter This is mounted in the case shown in Fig. 5

Setting up the selector relay closes a circuit to the opposite tube relay contacts enabling that relay, when energized by interruption of its associated light beam, to energize the proper counter circuit and complete the count. As soon as the second beam has been interrupted the count is made and the selector relay is unlatched, restoring the system to neutral ready for the next count. Thereupon, in order to prevent the second beam, which is probably still being interrupted by the passing vehicle, from immediately setting up its own selector relay, a lock out relay is included in the circuit and connected in such a way that it is energized during the last part of the counting cycle and remains energized so long as the second beam is interrupted.

It will be noted there are two identical sets of relays necessary in order to provide a two-way count.

AUTOMATIC RESTORING CIRCUIT

Occasionally, for some reason, only one beam is interrupted, and therefore the selector relay is left set up. Whenever the selector relay is set up, it closes the heating circuit on a thermal restoring relay. In about thirty seconds this thermal relay closes the unlocking circuit to the selector relay, restoring it to neutral, and ready for the next

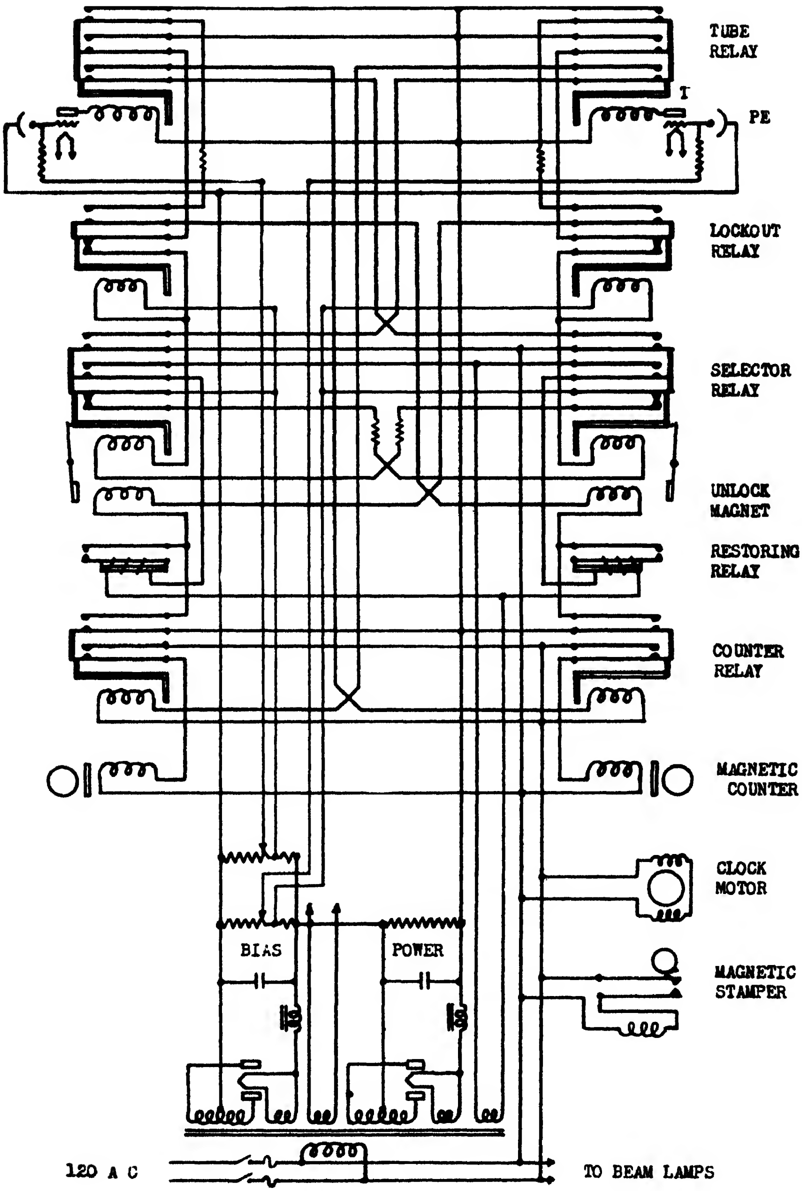

Fig. 7. Complete circuit diagram of the two-way recording traffic counter.

vehicle. This minimizes the possible error in counting which might otherwise occur.

COUNTING WHEN ONE LAMP IS BURNED OUT

If one light beam should be permanently interrupted its tube relay will be permanently energized and the total count in both directions will be registered on the other counter. Restoration of the light beam will restore the traffic counter to its two-way function.

NON-CHATTER DESIGN OF CIRCUIT

If one light beam is slowly intercepted, the bias voltage on the amplifier tube is slowly reduced until sufficient current will flow through the plate circuit to operate the relay. When this relay closes its contacts, one of the selective relays is also energized. The additional current drawn from the power supply causes a slight drop in plate voltage sufficient to cause the tube to drop the relay, and, upon the resulting rise in voltage, the tube again attempts to pick it up. Thus, under certain conditions of operation, especially during foggy weather, the counter will "chatter" continuously. This runs up a deceptive count.

To overcome this difficulty, connections were made so that the energizing of the selective relay imposes a new and additional positive bias of several volts on the grid circuit of the amplifier tube. (See Fig. 8.) This conteracts the voltage regulation of the power supply, and causes the relays to "snap in" and "snap out" positively and with no suggestion of chatter.

RAY FILTERS

Since PE cells selected for use in a traffic counter are sensitive to infra-red light almost as much as to white light, the operation of the counter is not seriously hampered by the use of infra-red filters. Therefore, the light rays are made invisible by means of such filters, thus reducing the inclination of passers-by to tamper with the counter. Such filters are usually located between the lamp and its focusing lens. (See Fig. 3.)

EXCLUSION OF EXTRANEOUS LIGHT

In order to exclude all light except that coming along the path of the beam from the lamp across the road, an opaque shield with a

¼" aperture is placed between the PE cell and the lens. The parallel rays of light coming from across the road, focused by the lens through this aperture spread out to fall on the target or anode of the PE cell,

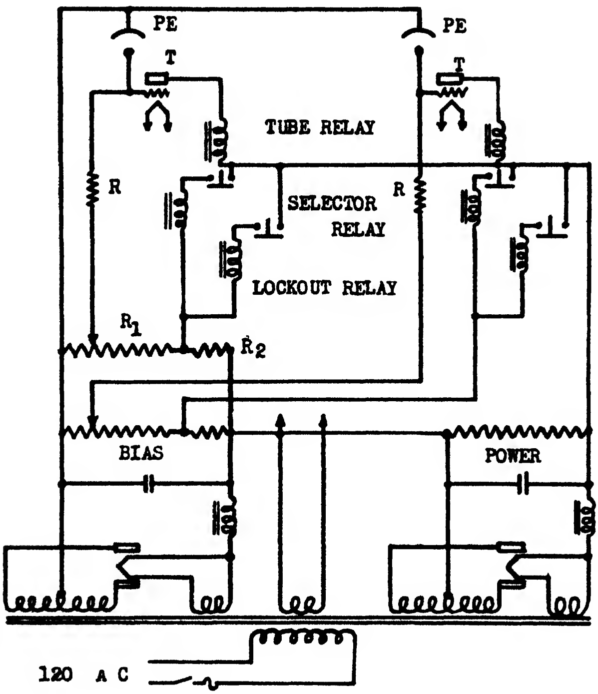

Fig. 8. Non-chatter feature of the traffic counter circuit. While the light beam illumines photo-electric cell PE, the current flowing through it and resistor R adds a negative voltage sufficient to bias the tube T to cutoff. As this bias is reduced by fog or a slow moving object across the light beam, plate current rises until it lifts the tube relay, which in turn closes the circuit on the selector relay. The current operating the selector relay flows from the power circuit through R_2, producing a positive voltage sufficient to partly cancel the bias voltage in R_1 and thereby raise the plate current through T above the critical value where chattering would have occurred.

but light other than from the lamp does not get through the aperture. Under certain circumstances, a white painted vehicle will reflect enough sunlight directly into the PE cell to replace the light of the interrupted beam with the result that no count is made. However, it is obvious that this error is negligible.

RECORDING MECHANISM

Provision is made for recording the traffic count on a continuous 4⅛" strip record. Driven by means of an accurate self-starting electric clock, the strip record is carried past the counters at the rate of ½" per hour. A drum with sprocket teeth engages the edge of the perforated record, thus affording a positive drive. Enough record for two months is carried on a spindle from which it is fed past the counters, over the drive roll, and onto a spring driven re-wind spool. Provision is made for easily removing the record and for inserting a new record. Penciled notations may be made on the record while still in the counter. Thus a maintenance man can note the time of his inspection and any other pertinent facts as to the condition of the counter.

USE OF WAX TYPE RECORD

Considerable difficulty is often experienced in the maintenance of an ink type pen. This was eliminated by the use of a wax coated record, made by the Stylograph Company of Rochester, N. Y This consists of a black or a red paper covered with a thin layer of gray wax. This leaves a gray surface and when the wax is removed by a stylus, a black or red line shows through. Therefore, a stylus replaces the pen, and no inked ribbon is required under the figure wheels as the figures are imprinted directly in the waxed surface Such a record is entirely legible and reliable.

MAGNETIC COUNTERS

Two five-wheel magnetic counters are mounted over the strip record—one at each margin One indicates right-bound traffic and the other left-bound traffic. These are actuated by 110 volt A. C electro magnets which in turn are controlled by means of A.C. power relays The counter wheels are of the raised figure type suitable for stamping the count on the record

PERIODIC STAMPING OF TOTALS

Geared to the clock motor is a switch which once each hour actuates an electro magnet which lifts a platen against the figure wheels to imprint the count on the record. The strip record passes between the platen and the counters, and therefore, is in position to receive the count at the proper time. Stamping is done on the hour.

CURVE OF TRAFFIC DENSITY

An auxiliary switch on each counter is closed momentarily upon the completion of every tenth count. This switch closes a circuit which causes a pen, so located as to scribe a line down the center of the chart, to make an excursion to the side of this straight line. Left-hand excursions indicate left-bound traffic by tens and right-hand excursions indicate right-bound traffic. Thus a group of ten excursions during the first half of an hour indicates that 100 cars passed the counter in that time, and the direction is indicated by which side of the line the excursions occur.

ERRORS IN OPERATION OF COUNTER

If two cars pass each other in front of the counter, only one of them will be counted, the direction depending on which beam is interrupted first. If, for some reason, one beam is interrupted and the other is not, then after about thirty seconds, a thermal switch unlocks the selective relay and restores the system to neutral without registering a count.

Sometimes a trailer will set up the selector relay as it interrupts the second beam after the car has completed the count If a second car follows within thirty seconds it will be counted in the wrong direction, and in turn will leave a selector relay set up However such errors will largely compensate themselves. Furthermore, such occurrences are reduced by the diagonal placing of the light beams across the road as shown in Fig 4 and Fig. 5.

APPENDIX

In order to increase the usefulness of this report to those interested in traffic counters, it seems desirable to include a brief description of the selective non-directional type of counter now commercially available and being used in considerable numbers. This decision was further influenced by the fact that full information on the circuits of such counters has not been available to the traffic engineer for maintenance purposes from any source whatsoever.

The following information and suggestions were obtained through the courtesy of the Washington State Highway Department

SELECTIVE TYPE COUNTER

The basic circuit diagram of the selective, non-directional type of counter is shown in Fig. 3. In Fig. 9, is shown the detailed circuit diagram of the I.B.M. counter, including amplifying and power tubes needed to operate it when the light source is a considerable distance away. The resistance values as shown, in many cases are not critical. This means that the circuit would operate equally well, for instance, if the 8 megohm resistors were replaced with 7 megohm resistors, etc. Condenser values are all in micro farads.

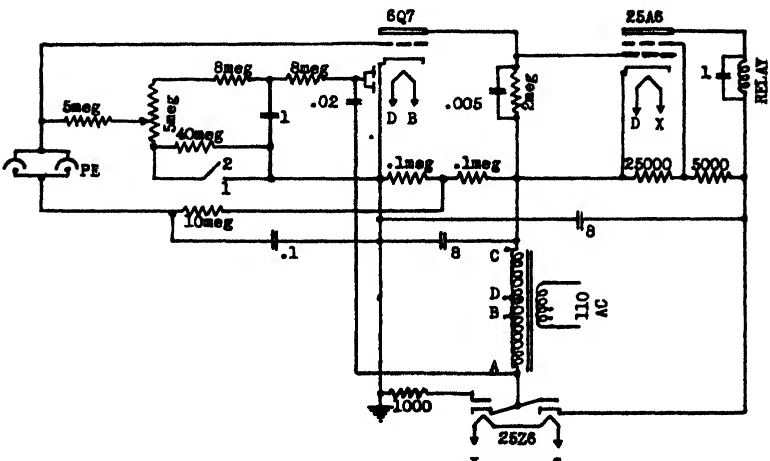

Fig. 9. Tube circuit diagram for the I.B.M. selective type counter. Light to the two photo-electric cells, connected in parallel, must be interrupted simultaneously in order to register a count. Such a counter will not register pedestians and will not recognize the spacing between a truck and trailer unless it exceeds three feet. Note that the dual element rectifier tube functions as two separate rectifiers, using the same A.C. source during opposite halves of the cycle, and that each of the two 8 mfd condensers stores energy during the active half of its cycle and yields this energy to its circuit during the other half. This simulates full wave rectification in both circuits.

The circuit diagrams are not shown for the associated printer magnets, time switch, etc., as these are not specially intricate, and furthermore, are already available to the maintenance man.

INSTALLATION OF TRAFIC COUNTERS

Fig. 10 and Fig. 11 show typical installations of traffic counters. Whenever practical, they are located near curves where there will be a minimum of cars overtaking and passing each other.

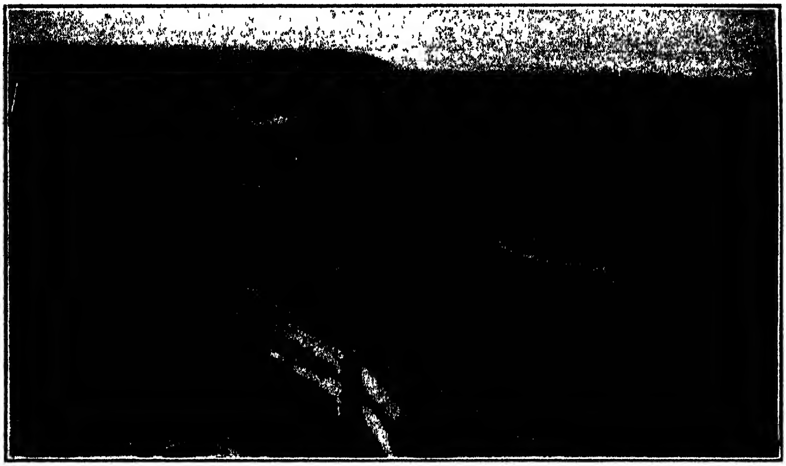

Fig. 10. Typical installation of a selective, non-directional type of counter located on U. S. Highway No. 410, near Wallula, Wash. Guard rails are found necessary to protect the counter from injury by vehicles running off the pavement.

Guard rails or fences are a practical necessity and in the end are proving an economy. In one instance, a traffic counter is mounted on concrete pedestals in a 4 foot ditch, clear off the shoulders of a straight highway where the view is in no way obstructed. Twice, in as many months, vehicles out of control, left the road and tore the counter from its foundation, damaging it considerably.

INCREASING LAMP AND TUBE LIFE

Experience has shown that a 6 volt automobile headlamp bulb, when operated at 6 volts A.C. will last about two weeks. However, if the A.C. voltage is reduced to about 4.5, a life of several months' continuous use is obtained with little reduction in the infra-red light beam.

In the I.B.M. counter, the 25Z6 rectifier tube is frequently the first to burn out. When adjusting the potentiometer, if it is turned just a little past the point where instructions say to stop, the life of the rectifier is materially increased. This adjustment does not appear to affect the sensitivity or accuracy of the counter.

COUNTERACTING EFFECTS OF MOISTURE

Under conditions of high humidity, or considerable changes of temperature, moisture may collect on lenses and mirrors of the optical

Fig. 11. Note the damaged guard fence, provided to protect the counter mechanism from injury by passing vehicles. The light beams are invisible to pedestrians or passing motorists at all times, due to the use of infra red filters. Power for the opposite unit is supplied through a conduit underneath the roadbed. The nearest unit is the light source, the other is the light receiver and counter mechanism.

system, causing failure or erratic operation of the counter Current leakage due to collection of moisture on the base of the photo-electric tube gives the same result. Such difficulty has been remedied by the installation of a small resistance unit under the lens or next the tube base, and connected to the A.C. circuit to act as a heater.

FAILURE DUE TO TRAFFIC VIBRATION

The passage of heavy freight traffic often sets up considerable vibration in the entire traffic counter unit. This is due both to ground vibration from the vehicle, and to air vibration due to motor exhaust. Many instances of erratic counting, or complete failure have been traced to broken leads or loosened solder connections in the counter circuits, which apparently were due to repeated vibration. Loosening of contact screws, or of screw adjustments may occur from the same cause.

TROUBLE FROM EXTRANEOUS LIGHT

When a traffic counter must be located on a north-south highway, unwanted light from the sun in early morning, or late evening may enter the optical system to interfere with correct counting. Installation of long tubular shields over the receiver lens frequently is suffi-

cients to correct this trouble. Reducing the size of the aperture at the focal point of the receiver lens is also sometimes necessary. Use of either one or both of these devices has made it possible to install a traffic counter at practically any desired location.

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Torsional Stress Concentration Factors at Fillets

by James G. McGivern
Assistant Professor of Mechanical Engineering

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ENGINEERING EXPERIMENT STATION
H V. Carpenter, Director

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by James G. McGivern

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ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

STATE COLLEGE OF WASHINGTON

Pullman, Washington

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Torsional Stress Concentration Factors At Fillets

I Introduction

It has been known for some time that abrupt changes in the shape of shafting cause stress concentrations and that these highly localized stresses account for many of the failures experienced in practice. Whether the loading of the shaft be axial, transverse, or torsional, the maximum stress corresponding to each form of loading will be higher at the place of change in shape than in a straight part of the shaft adjacent to this location. This degree of concentration (the ratio of the concentrated stress to the average stress) for various shapes and sizes of shafting is a very important item for efficient design.

The actual computing of these concentration factors by applying the ordinary equations of elasticity is either impossible or impractical except for the very simplest of geometrical shapes. Because of this limitation of the mathematical theory it is necessary to resort to various experimental solutions for the determination of the stress conditions in rods having non-circular shaped cross-sections, and in uniform circular cross-sections with keyways cut in them, and in circular rods having abrupt changes in cross-section in the axial direction.

It is this latter problem of determining the relative effects of the fillet and shaft diameters on the torsional stress concentration factors and on the shaft rigidity with which this report is concerned. These results are based on a study of the plastic flow characteristics of mild steel as revealed by actual stress strain diagrams of specimens having various ratios of large to small diameters of shafts and of fillet radii to small diameters. The general principle underlying the basis of the plastic flow method is discussed as is the method used for testing. Some macro-etched specimens of twisted rods are included to illustrate the mechanism of plastic flow. The effect of fillets on the shaft rigidity is also worked out. The concentration factors are given in graphical form, together with an empirically derived equation which fits the experimental values with a reasonable degree of accuracy. These final results are compared with concentration factors determined by other methods.

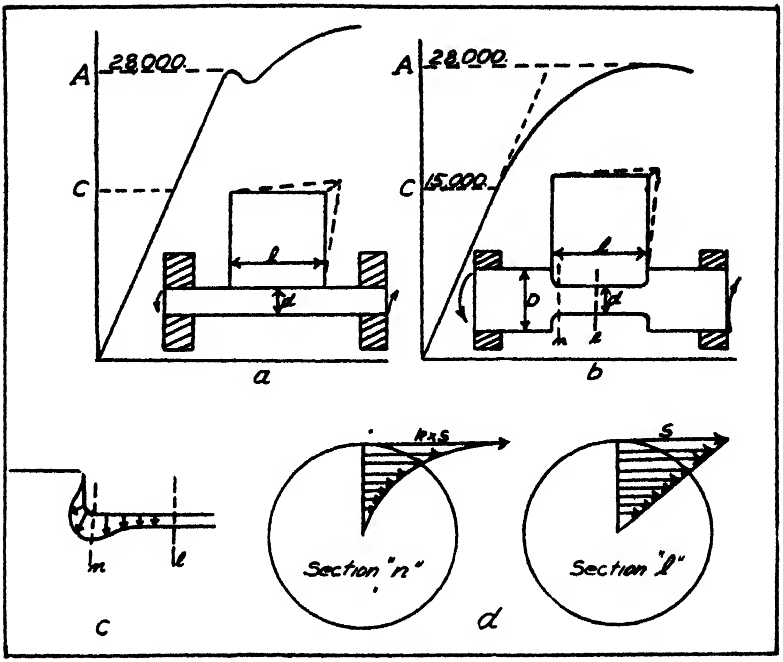

Fig. 1 Basis of Plastic Flow Method.

II Principle of the Plastic Flow Method

Fig. 1a represents the stress strain characteristics of a SAE-1020 steel subjected to torsion. In this diagram the ordinates represent the shear stress in the outer fibre of a uniform rod as determined by the simple equation:

$$S = \frac{Mr}{I} \qquad (1)$$

where S, M, r and I are respectively the shearing stress in the outer fibre, the twisting moment, the radius of the shaft and the polar moment of inertia of the shaft. The abscissae represent the angle of twist per unit length of the shaft expressed in radians per inch. This diagram is a typical one, and it is seen that this material follows Hooke's law of proportionality to the upper yield point "A" and then yields appreciably without further increase of stress. From this observation the generalization may be made that when any part of a specimen of

this material has reached a stress equal to the yield value then appreciable deformation will take place at the region subjected to this shear stress. It is also of importance that the converse would be true. This means that at any place in a specimen of this material where we find large deformations the stress associated with this deformation must be equal to the yield stress. The simple principle may now be applied to the determination of torsional stress concentrations.

Fig 1a and 1b represent two torsional stress strain diagrams of SAE-1020 steel. For the first case the angle was measured between sections two inches apart on the uniform diameter as illustrated in Fig. 1a. In the second case, the angle was measured between the shoulders where the fillets join the large shaft "D," as shown in Fig. 1b. The difference between the two set-ups is that in the second case the two inch gage length includes two fillets. In comparing the two diagrams it is seen that both have their stress strain relations linear to stress "C." At this point the uniform specimen indicates that the stress of (C) lbs./sq. in. is below the yield value, whereas at this same stress the specimen containing fillets begins to deviate from Hooke's Law of Proportionality. This indicates that the region around the fillets has reached the yield stress and plastic flow has taken place. With continued application of more moment the area at the fillet will continue yielding causing it to deviate more and more from the stress strain diagram of the uniform shaft until the stress in the outer fibre at a distance removed from the fillet reaches the yield stress. At this time the shaft will yield very markedly and behave very similar to the uniform shaft after it has begun to yield, with the exception of the increased cold working effect that has already taken place at the fillets.

The degree of stress intensity or the value of the stress concentration factor "k" for the case used is equal to the true yield stress of the material represented by "A" in Fig. 1a divided by the stress corresponding to plastic flow represented by "C" in Fig. 1b. This is numerically equal to 28,000 lbs./sq. in. divided by 15,000 lbs./sq. in., or 1.86. Physically this means that below the yield stress the stress at the fillet will be equal to 1.85 or "k" times the stress at another point on the surface of the shaft far removed from the fillet. This place of maximum shear stress is located just where the fillet radius is tangent to the small shaft and is caused by the complex stress relations ac-

companying the warpings of the originally plane cross-sections near the fillets. The distribution of shear stresses along the surface of the shaft is given in Fig. 1c where the maximum stress at section "n" is equal to "k" times the stress at the same radius on section "1." This follows since the two sections must resist the same twisting moment meaning the stresses near the center of section "n" must be less than those at "1." This results in a non-linear distribution at "n" compared to the assumed linear distribution as indicated in Fig. 1d.

In evaluating the stress concentration factor the yield stress "A" of the uniform shaft was taken as the basis of comparison rather than the proportional limit which is below the yield stress. This was done since the ration of the yield stress to the proportional limit may be taken as representing any concentration factor due to material, working or heat treatment.[1] By using the yield stress the total concentration factor is given which includes the material as well as the shape factor The concentration value as determined for the material alone and equal to the ratio of the yield stress to the proportional limit, had an average value of 1.06.

III Testing Procedure

Specimens. The specimens were prepared from 2″ and 2¼″ diameter hot rolled SAE-1020 steel. The yield strengths of specimens cut from different rods and from various parts of the same rod varied considerably as shown in Table I. For the materials used, including those which were annealed, it was found that the yield strengths as obtained from uniform diameter specimens varied from 30,000 pounds per sq. inch to 14,000 pounds per square inch. In the first tests uniform specimens were made from stock adjacent to those from which the specimens with fillets were prepared. The true yield strengths were taken from the uniform diameter specimens and divided by the stress represented by "C" of Fig. 1b for obtaining the stress concentration factor. After a few tests it became evident that the yield stress as determined from the uniform specimens varied very little from that corresponding to "A" of Fig. 1b, of the concentration specimen. Since the deviation from this value was small and both positive and negative, the stress of uniform yielding of the rod with the fillets was taken as

[1] Temoshenko, S. and Lessells, J. M., "Applied Elasticity"; Westinghouse Tech. Sch. Press, 1925, p. 412.

TABLE I

No.	Min. Shaft Dia.	2r/d	Plastic Flow Stress	Yield Stress	Stress Con. Factor "k"	Slope of Modulus Line	G/G_1	$\Delta l/l$	Δl
				$D/d = 2.5$					
246	.740	.162	13,000	20,800	1 60	11,400,000	1.19	.19	.38
247	.740	.101	15,000	24,500	1.63	11,570,000	1.17	.17	.34
239	.740	.490	15,500	28,500	1.84	12,000,000	1.03	.03	.06
234	.740	.495	20,000	25,000	1.25	11,350,000	1 09	.09	.18
235	.740	.0123	13,800	22,300	1.62	11,100,000	1.11	.11	.22
240	.740	.0825	13,800	25,080	1 81	10,950,000	1 13	.13	.26
233	.740	.0	8,800	23,200	2.64	11,500,000	1.22	.22	.44
236	.739	.235	16,800	23,000	1.37	11,900,000	1 08	08	.16
237	.730	.400	14,400	23,400	1 61	11,960,000	1.04	04	.08
254	.740	.12	12,700	25,100	1.97	11,100,000	1.10	.11	22.
255	.740	.326	14,200	22,000	1 55	11,150,000	1.11	.11	22
				$D/d = 2\ 0$					
55	.926	.0637	16,400	30,300	1.85	11,700,000	1.05	.05	.10
56	926	.308	24,500	29,800	1.22	12,280,000	1 1	10	.20
58	.926	.193	17,800	29,100	1.63	11,100,000	1.116	116	.232
59	.926	.312	22,000	30,300	1 37	12,600,000	0,985	.015	.03
60	.926	400	22,800	30,300	1 33	12,830,000	.965	035	.07
65B	.926	.092	16,400	29,400	1.79	10,950,000	1.132	.132	.264
66B	.927	.0638	14,100	25,500	1.81	10,340,000	1 2	.2	.4
67B	.854	.142	20,800	30,300	1.46	13,000,000	.955	.045	.090
74	.922	.201	14,300	20,800	1 45	11,700,000	1.06	06	.12
105	.911	.0	5,950	24,800	4.17	10,800,000	1.148	148	296
				$D/d = 1.5$					
35	1.235	.06	17,500	30,300	1.73	11,100,000	1.12	.12	.24
38	1.235	.0825	16,800	29,100	1.73	11,200,000	1 11	.11	22
39	1.234	.143	18,200	28.500	1.56	11,050,000	1 12	12	.24
40	1.235	.163	18,200	29,100	1.60	11,280,000	1.10	10	.20
41	1.234	.17	18,200	28,800	1.58	11,050,000	1.12	12	.24
42	1.234	.098	18,600	28,100	1.51	10,570,000	1 175	.175	.350
43	1.234	.253	23,000	28,800	1.25	11,150,000	1.112	.11	.22
44	1.235	.0478	15,100	29,550	1.96	10,870,000	1.14	.14	.28
52	1.235	.246	21,200	28,400	1.34	11,330,000	1 10	.10	.20
53	1.234	.047	16,000	29,700	1.86	10,580,000	1 175	.175	.350
61	1.245	.1483	17,200	28,300	1.65	10,850,000	1.145	.145	.290
68	1.228	.151	14,100	22,200	1.57	10,890,000	1.14	.14	.28
69	1.221	.0632	15,600	21,650	1 39	10,500,000	1.18	.18	.36
73	1.226	.0432	12,500	23,450	1.88	11,150,000	1 11	.11	.22
80	1.228	.151	16,100	22,100	1.38	11,650,000	1.065	.065	.130
104	1.233	.0	7,200	24,700	3.43	11,100,000	1.128	.128	.256

TABLE I (Continued)

	Min. Shaft Dia.	2r/d	Plastic Flow Stress	Yield Stress	Stress Con. Factor "k"	Slope of Modulus Line	G/G_1	$\Delta l/l$	Δl
				D/d = 1.33					
12	1.397	.079	8,800	14,100	1.60	10,550,000	1.177	.177	.35
13	1.393	.071	15,500	25,800	1.66	11,250,000	1.10	.10	.20
14	1.393	.113	18,600	26,850	1.44	11,000,000	1.13	.13	.26
15	1.393	145	19,400	24,800	1.28	10,850,000	1.14	.14	.28
16	1.393	.0502	14,400	25,800	1.79	11,000,000	1.13	.13	.26
17	1.392	.239	14,800	19,200	1.29	11,140,000	1.09	.09	.18
25	1.393	.0323	13,300	21,800	1.64	11,350,000	1.093	.093	.186
32	1.393	.0423	16,500	30,400	1.84	11,150,000	1.11	.11	.22
65	1.380	.0565	13,000	22,600	1.74	11,260,000	1.10	.10	.20
66	1.330	.138	15,000	21,900	1.46	12,400,000	1.00	.0	.0
67	1.331	.206	16,800	21,750	1.29	11,800,000	1.05	.05	.1
71	1.385	.133	15,600	20,000	1.28	11,100,000	1.12	.12	.24
103	1.385	.0	13,000	38,800	2.98	10,000,000	1.08	.08	.16
100	1.393	.064	18,000	31,500	1.75	12,200,000	1.02	.02	.04
				D/d = 1.2					
19	1.545	.044	13,200	19,950	1.51	10,800,000	1.15	.15	.30
20	1.545	.130	14,800	20,550	1.39	10,860,000	1.142	.142	284
21	1.545	.104	12,400	17,500	1.41	11,020,000	1.124	.124	.248
22	1.545	.187	16,200	18,750	1.16	10,770,000	1.152	.152	.304
23	1.542	.216	15,200	18,750	1.23	11,100,000	1.115	.115	.330
26	1.545	.0362	12,800	20,000	1.56	10,770,000	1.152	.152	.304
27	1.545	.115	17,200	20,100	1.17	11,490,000	1.082	.082	.164
28	1.545	.077	12,200	20,200	1.67	10,640,000	1.167	.167	.334
29	1.545	.206	17,600	19,800	1.12	11,700,000	1.06	.06	.12
33	1.545	.077	20,400	26,800	1.31	10,220,000	1.21	.21	.42
37	1.545	.055	19,600	29,000	1.48	10,790,000	1.155	.155	.310
54	1.545	.037	17,600	29,400	1.67	11,300,000	1.1	.1	.2
62	1.545	.322	24,000	27,750	1.15	12,160,000	1.02	.02	.04
63	1.545	.241	23,600	28,100	1.19	10,450,000	1.185	.185	.37
30	1.545	.067	9,300	18,700	2.01	10,560,000	1.172	.172	.354
102	1.545	.0	10,000	25,300	2.52	10,740,000	1.15	.15	.30
				D/d = 1.1					
31	1.684	.0743	19,650	25,800	1.31	11,800,000	1.05	.05	.10
36	1.393	.204	18,000	20,250	1.12	12,200,000	1.018	.018	.036
45	1.373	.043	20,000	28,350	1.42	12,350,000	1.005	.005	.01
46	1.393	.074	18,000	25,000	1.39	10,900,000	1.140	.14	.28
47	1.393	.109	22,100	27,750	1.25	11,950,000	1.040	.040	.08
48	1.393	.086	21,800	29,600	1.36	12,300,000	1.01	.01	.02
49	1.393	.208	20,300	23,800	1.17	12,000,000	1.03	.03	.06
50	1.393	.063	21,000	28,350	1.35	12,000,000	1.03	.03	.06
51	1.393	.176	21,000	26,400	1.26	11,800,000	1.05	.05	.10
81	1.328	.177	17,800	21,450	1.20	12,630,000	1.02	.02	.04
88	1.393	.0	9,200	24,800	2.70	11,950,000	1.04	.04	.08
89	1.393	.071	16,200	24,800	1.53	11,600,000	1.07	.07	.14

representing the true yield stress. This saved considerable time as well as eliminating the possible variation in material between specimens. The final curves drawn through the average of the points are believed to be the same as would have been obtained by the longer method.

The specimens were so made that in all cases the diameters of the large shafts were either 1.85" or 1.53". This larger value was conditioned by the maximum size of the jaws of the testing machine. The shoulders of the large shafts were two inches apart. The most difficult part in preparing the specimens was the machining and measurement of the small fillets. This was accomplished by brazing ball bearings on to the end of steel stock. The top of the balls were then carefully ground down giving an accurately machined circular cutting tool whose diameter could be easily and accurately measured. Fig 2 shows some of the tools so prepared. By this method it was possible

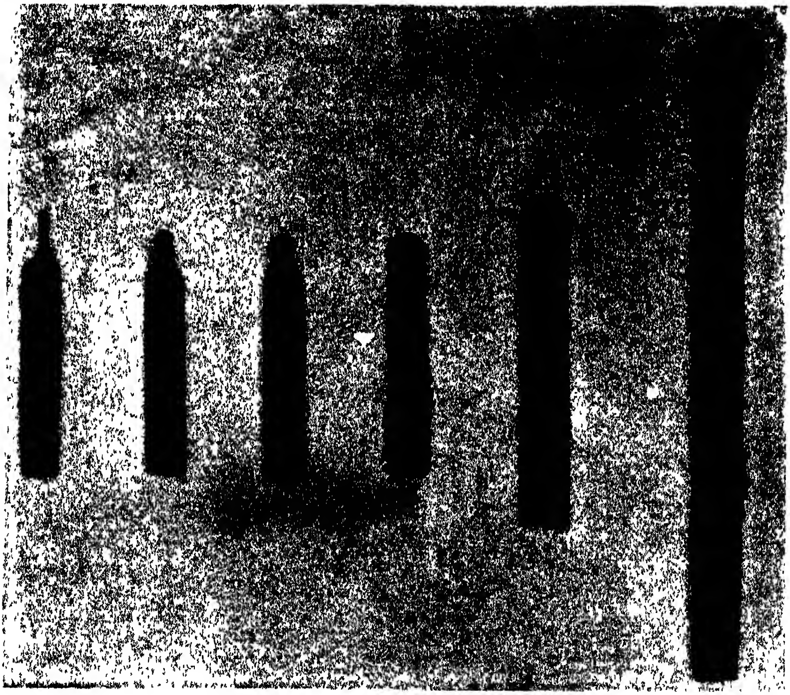

Fig. 2 Tools for Machining Fillets.

to get fillet radii as small as .027", which for the shaft diameters used made possible ratios of diameter of fillet tool to diameter of small shaft equal to .073 for a ratio of D/d as large as 2.5. For a ratio of D/d equal to 1.33 and greater, the difference between diameters was sufficient for the fillet radii to be tangent both to the small shaft and the square shoulder. For the diameter ratios of 1.2 and 1.1 the fillet radii were not always tangent to the square shoulder. This was true for the 1.1 curve when 2r/d was greater than .10 and for the 1.2 curves when 2r/d was greater than .20 where r equals fillet radius.

In machining the fillets it was found desirable to use a very slow cutting speed and fish oil as a cutting fluid. The cylindrical sections of specimens were machined to one-half of one thousandth of an inch and then given a high polish. Particular pains were taken in preparing all specimens as tests have been reported attributing much of the localized stress to surface condition.

The standard equipment used to measure the angle of twist was not accurate enough so the set-up as shown in Fig. 3 was constructed. The two arms seen in the picture are twenty inches long and two

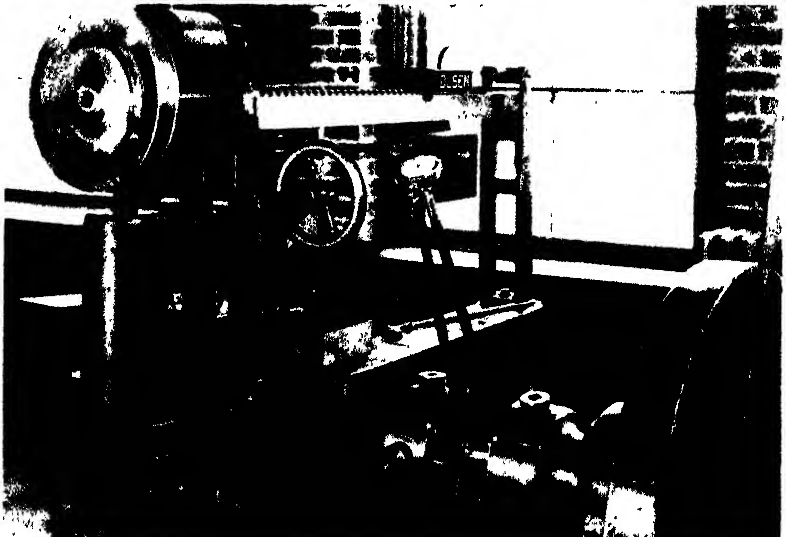

Fig. 3 Setup for Torsional Concentration Tests

inches apart. The dial micrometer for recording the relative displacement at the end of the arms was graduate in thousandths of an inch. The dial reading for determining the angle of twist was recorded for each 100 inch-pound increment for diameters smaller than .926 inches, and 150 inch-pound increment for diameters above that value. Then by use of equation (1) the stress of the outer fibres of the shaft at a point far removed from the fillet was calculated for each moment increment and stress strain curves similar to Fig 1a and 1b were plotted.

While the readings were being taken the speed of twisting corresponded to one-sixth of a turn per hour and was regulated by hand. After the specimen had yielded considerably and the stress in the outer surface far removed from the fillet had reached the yield stress, the instruments were removed and the rate of twisting regulated by the power drive Under these latter conditions the specimen was twisted to failure at a rate of one turn every fifty minutes.

IV. Interpretation of Stress Strain Curves

Some representative stress strain curves obtained from specimens having a ratio of large diameter to small diameter equal to 1.33 are given in Fig. 4. The lower stress values given on the curves represent the beginning of plastic flow, and were determined from diagrams

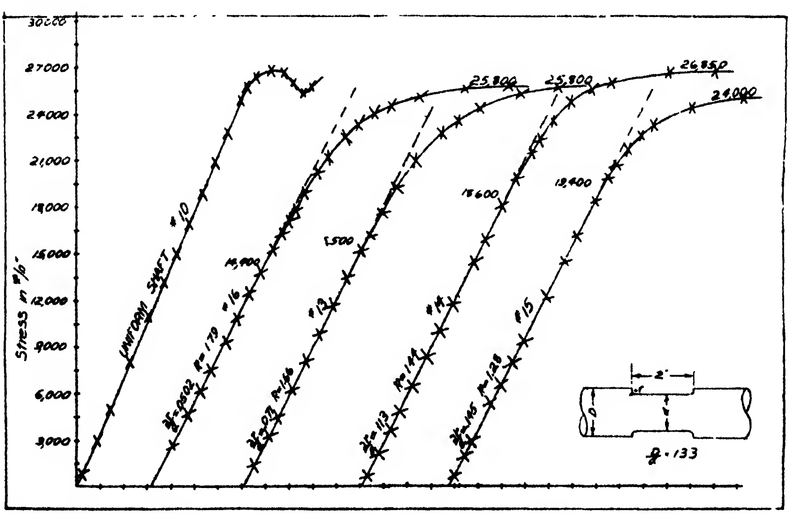

Fig. 4 Typical Stress Strain Diagrams for Determining Stress Concentration Factors.

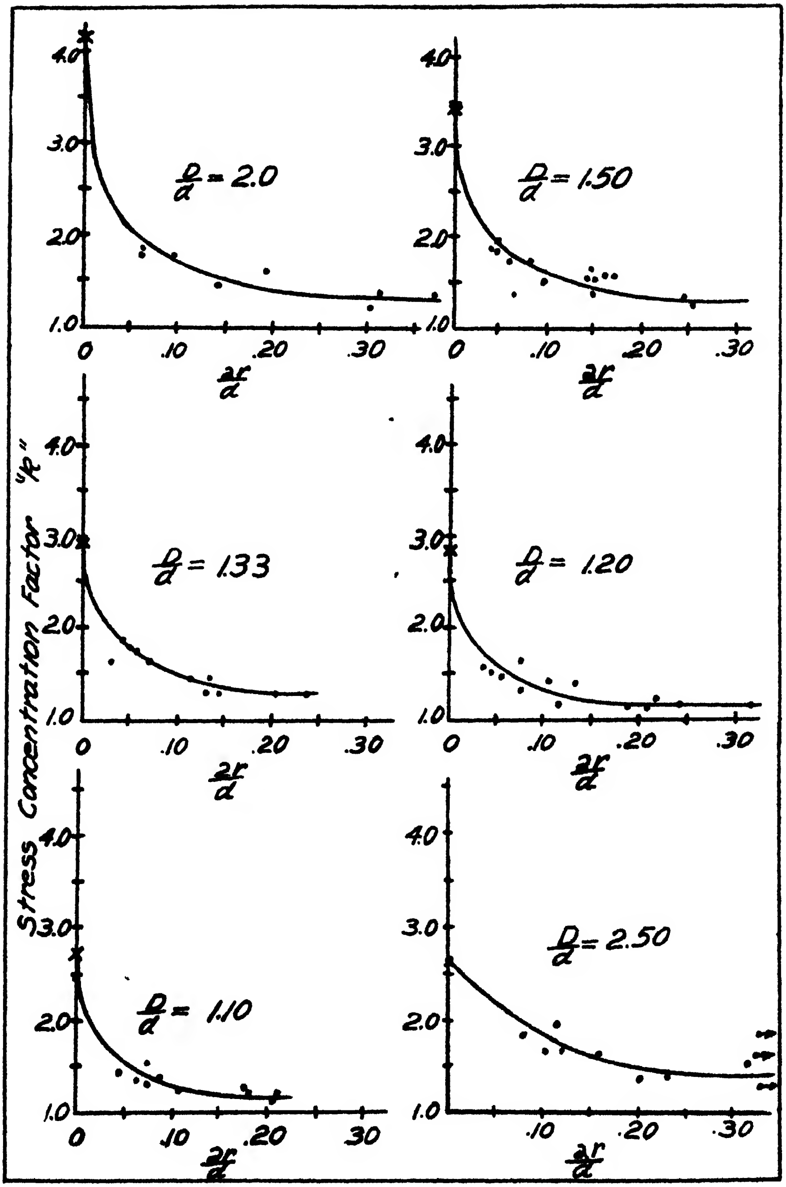

Fig. 5 Distribution of Stress Concentration Factors with respect to Average Curve.

drawn to a scale of one inch equal to 2,000 lbs. per square inch. This large scale was used for the determination of all values quoted in this report. The figure shows the gradual decrease in the plastic flow stress as the ratio of 2r/d decreases. The specimens represented were all cut from the same rolled stock and there is not much variation in the stresses corresponding to the uniform yielding. The yield values from all of the specimens having this ratio of diameters were not the same however as seen in Table I, but the stress concentration factors as determined from the curves for the various materials fall on a smooth curve. Table I gives the plastic flow stresses, the yield stresses, and the stress concentration factors for all the tests made. Fig. 5 gives the data in graphical form showing the distribution of the individual points with respect to the average curve.

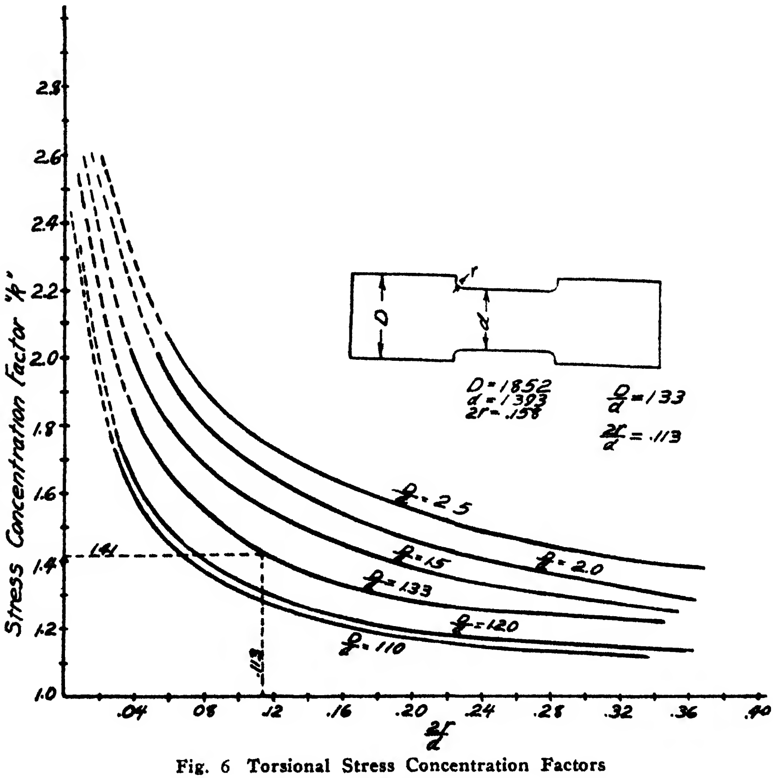

Fig. 6 Torsional Stress Concentration Factors

Fig. 6 gives, to a larger scale, all the curves of Fig. 5 and shows the effect on the concentration factor of the ratio of shaft diameters and of the ratio of fillet radius to small diameter. These curves are in a usable form as the curves and coordinates are expressed in terms of dimensionless ratios.

Whether these concentration factors are dependent upon the ratio of diameters and fillets alone and independent of actual sizes is still open to question. When stress concentrations are not present model testing appears to be justified. With stress concentrations, and especially those accompanying dynamic loading present, the results appear to vary with size, the small specimens tending to give higher values.[2 3] To have complete similarity not only would the geometric properties have to be considered, but also the modulus of elasticity, size and characteristics of crystal system, strain hardening characteristics, surface finish, loading conditions, and speed Until the laws concerning the transfer between the results from specimens of different sizes are better understood the dimensionless treatment appears to be the most suitable form.

The use of Fig. 6 is illustrated by the following example. Consider a shaft of four inches large diameter and three inches small diameter, having a fillet radius of .170. In this case the value of 2r/d equals .113 and the value of $D/d = 1.33$ The dotted lines of Fig. 6 indicates for this case a stress value equal to 1.41. This means that the torsional stress at the fillets is 1.41 times the torsional stress at the surface of the small three inch diameter shaft as calculated by equation1. For design purposes, the maximum allowable stress on the small uniform shaft should be equal to the maximum allowable shear stress of the material divided by 1.41 in order that the stress at the fillet shall not exceed the allowable working stress of the material used.

V. Shaft Rigidity

Table I lists the slope of the modulus line or the "apparent modulus of elasticity." This change in rigidity appears to be a function of the ratio of D/d and 2r/d. Rather than use a varying modulus of elasticity in complex shaped shafting it is common to use a con-

[2]Peterson, R. E. "Model Testing as Applied to Strengths of Materials"; Journal of Applied Mechanics, A.S.M.E., Vol. 4, 1933.

[3]Nadai, A. and MacGregor, C. W., On Laws of Similitude in Material Testing"; A.S.T.M., Vol. 34, part II, p. 216, 1934.

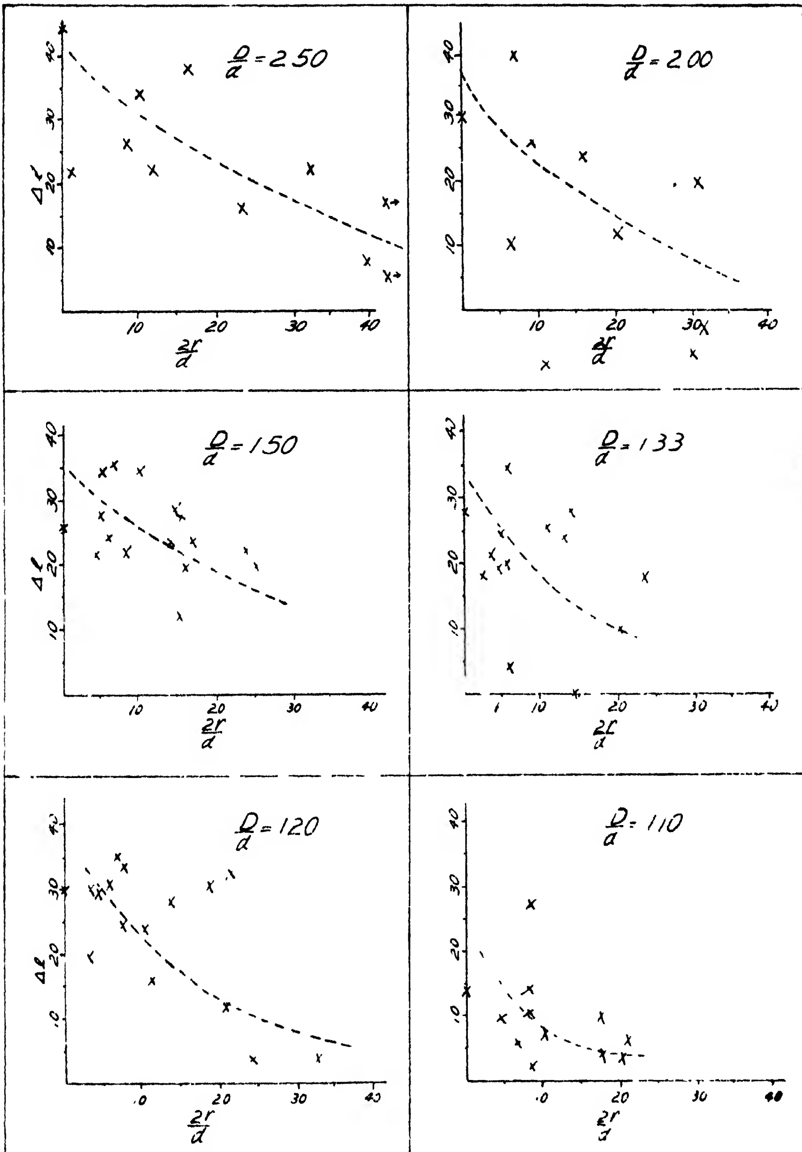

Fig. 7. Length Increment as Effected by Diameter Ratio and Fillet Radius.

stant modulus and change the dimensions of the shafting. From our data it is possible to determine the increment of length to be added to the original length for using the true modulus of elasticity in calculating the angle of twist. By denoting the increment of length "Δl," the apparent modulus of specimens with fillets "G^1," the true modulus "G," the moment of inertia of the small uniform shaft "I," and the applied twisting moment "M" we have by applying the Coulomb equation:

$$\frac{M(l+\Delta l)}{GI} = \frac{Ml}{G^1 I} \quad \text{or}$$

$$\frac{\Delta l}{l} = \left(\frac{G}{G^1} - 1\right) \tag{2}$$

The "Δl" referred to is the amount to be added to the small shaft when two fillets are present. For the case of one fillet one half of this amount would be used. Table I gives the values for this length increment for all of the specimens tested. The values in the table were calculated taking the true modulus of elasticity as 12,400,000 lbs. per sq. in. The ratio of the increment of length to the length of the shaft is plotted against the ratio of the fillet diameter to the shaft in Fig. 7. Thus it is possible to disregard the fillets and add "Δl" to the distance between the shoulders and calculate the angle of twist of the new simplified shaft of equivalent rigidity by using the value of 12,400,000 lbs./sq. in. for "G" and the value of $(l+\Delta l)$ for l in the simplified Coulomb equation. This reduction of complicated shapes to equivalent shafts of uniform diameter is very convenient when computing the natural frequencies of rotating machinery.[4] [5] This value of "Δl" is not a constant for all lengths, and further work is being done in determining how it varies with length which will be reported at a later date. The large deviation of the values from the assumed average curves drawn in Fig. 7 are due in part to the inaccuracy inherent in Equation 2. This equation shows that as the ratio of modulii approaches unity a small change in its value will produce a relatively large percentage error in the length increment. The average modulus of elasticity of 12,400,000 lbs. per square inch used in the determination of the modulii ratio

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[4] Temoshenko, S. "Torsion of Crankshafts"; A.S.M.E., Vol. 44 (1922), p. 653.

[5] Porter, F. P. "Range and Severity of Torsional Vibrations in Diesel Engines," A.S.M.E., APM 50-8, 1928.

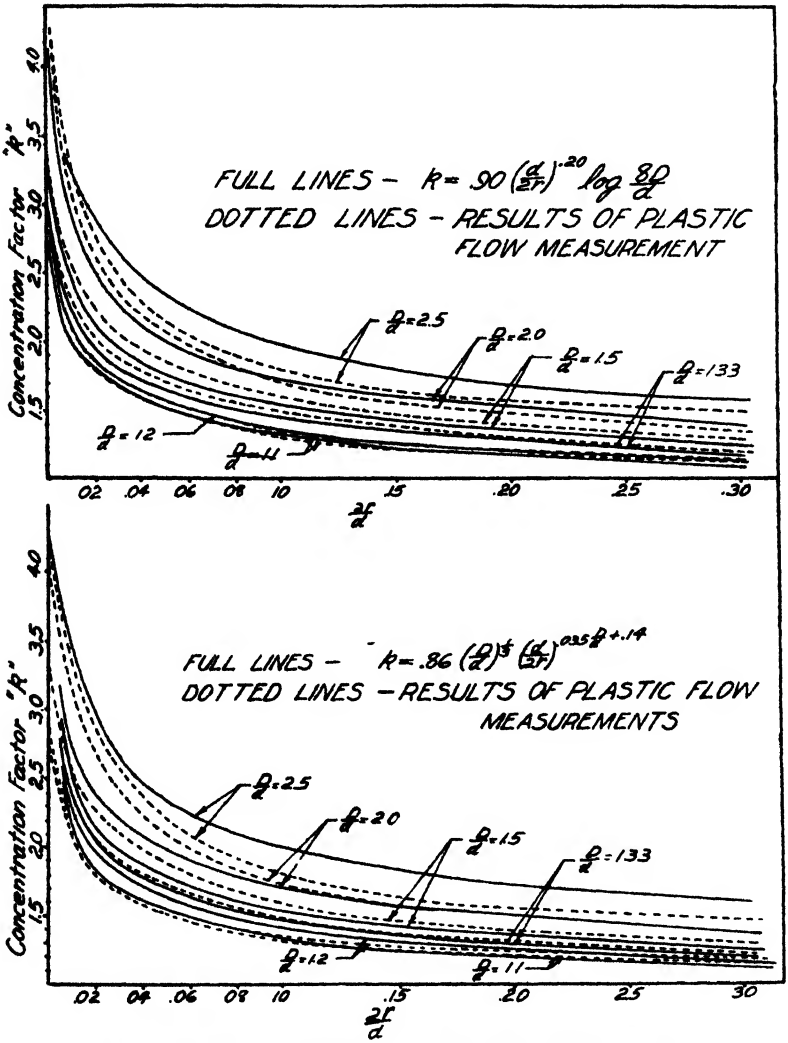


Fig. 8 Comparison of Test Data with Emperical Equations

appears to be high. This was the average value obtained from uniform specimens using a two-inch gage length. In using this value it would be necessary to take the modulus of elasticity in tension as 31,000,000 lbs. per square inch to obtain a reasonable value of Poisson's ratio for mild steel.

VI. Empirical Equations for Stress Concentration Curves

These experiments include an investigation of the values of diameter and fillet ratios that would be used in shaft design. Instead of using the curves of Fig. 6 for obtaining stress concentration values for design, the two following equations are given as fitting the test results with a sufficient degree of accuracy.

$$K = .86\sqrt[3]{D/d}\;(d/2r)^{.14+.035\ D/d} \tag{3}$$

$$K = .9\log(8\,D/d)\;(d/2r)^{.20} \tag{4}$$

Fig. 8 gives a comparison of the actual test curves, obtained from the plastic flow method, with those obtained from equation 3. The experimental curves are represented by dot and dash lines. The full or equation lines extend to infinity when the fillet radius becomes zero but at a value of 2r/d equal to .005 the agreement between the two sets of curves is very good and this fillet ratio is smaller than would be used in practice. The equation also gives stress concentration values less than one for very large values of 2r/d but again these values are outside the practical limit. For using the equation for values of the ratio of diameters greater than two, the concentration values obtained would be larger than the true values. In the extreme case where a shaft would join into a plate the ratio of diameters would be very large and the formula gives values considerably higher than the true values. Stress concentration values for the extreme case where the ratio of large to small diameter is taken as equal to infinity have been worked out using the graphical method originally proposed by Willers.[6] This result varies but little from the plastic flow results, for the case where the large diameter equals twice the small diameter

The agreement between equation (4) and the plastic flow results are given in Fig. 8b For the lower values of the ratio of diameters this equation does not fit the results as well as equation (3), but for the ratio equal to 1.33 the curve fits almost exactly.

VI. Position and Angle of Fracture

The type of fracture obtained was of interest and revealed the actual plane of failure to be at the beginning of the fillet on the small shaft and that this plane of failure was not perpendicular to the axis

[6] Willers, F. A. "Z. Math Physik," Vol. 55, p. 107.

of the shaft. The location of the fracture coincides with the position of maximum stress as obtained from studies confined to idealized conditions. The cold working accompanying the plastic flow of the material after reaching the yield stress had evidently not changed the stress distribution to the extent that the location of the plane of maximum stress had changed. This position of the failure starting at the beginning of the fillet was clearly seen when large fillets were used and, after the fracture occurred at one of the fillets, cracks could be observed at the other fillet.

In a circular shaft of uniform diameter subject to pure torsion, the plane of maximum shear stress is normal to the axis of the shaft The planes of maximum tension and compression are 45° from this plane of maximum shear stress, or 45° from the axis of the shaft. These maximum tension and compression stresses acting on the 45° planes are both equal in magnitude to the maximum shear stress. When the diameter of the shaft is no longer uniform and a fillet is introduced, the direction of the maximum shear and normal stresses are no longer respectively normal and 45° to the shaft axis. In the region of the fillet the planes normal to the shaft axis before twisting become warped upon application of a twisting moment and complex stress conditions result. Fig. 9 shows, as a result of this condition, that the plane of failure, or the plane of maximum shear stress for

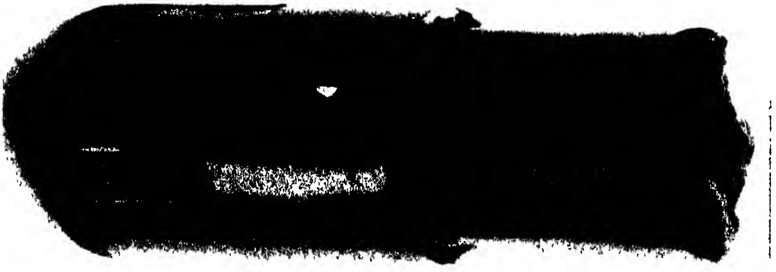


Fig. 9 A Typical Fractured Specimen

a ductile material, makes an angle other than 90° with the shaft axis. This angle varied with the specimens tested, depending upon the ratio of diameters and the size of the fillet radius used. In addition to the angle of fracture Fig. 9 shows the crater, at the center of the shaft.

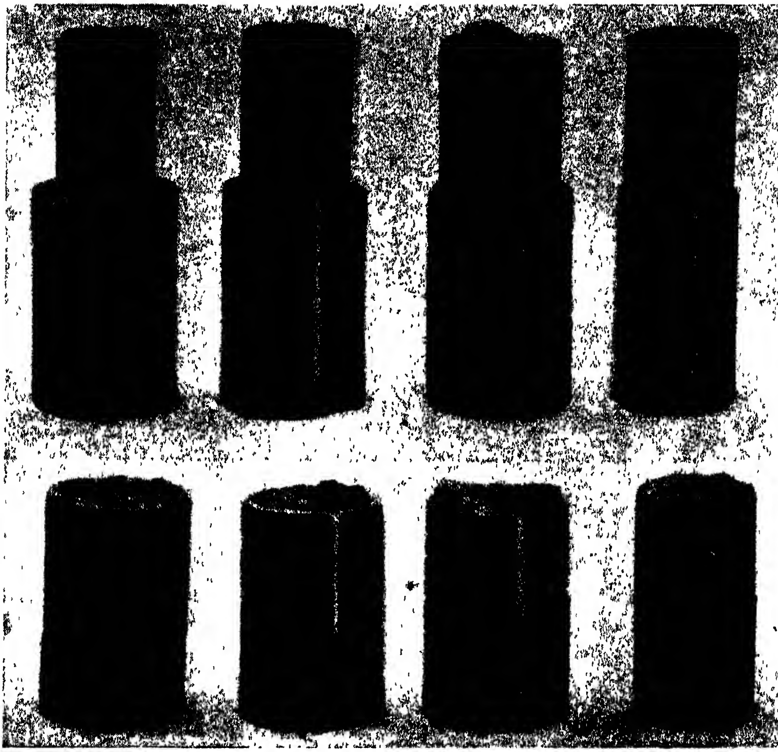


Fig. 10 Fractured Specimens Having Various Ratios of Diameters

This last place of breaking had the appearance of a pure tension break on a plane approximating 45° and could be observed in all of the specimens.

Fig. 10 shows the angle of fracture and the crater effect for specimens having ratios of diameter varying from 1.50 to 1.10.

As a further check on this angle of fracture some cast iron specimens were made. Cast iron being weaker in tension than in shear will fail when the maximum diagonal tension stress reaches the tensile strength of the cast iron. By twisting cast iron specimens to failure it is possible to determine how much the plane of the maximum tension stress deviates from making an angle of 45° with the shaft axis when the failure occurs at the fillets. This angle may then be com-

pared with the angle of maximum shear as obtained from a mild steel specimen of the same proportion to see whether the plane of maximum tension and shear are 45° apart. Such a comparison is given in Fig. 11 which shows two sets of steel and cast iron specimens, the set at the left having comparatively small fillets and the set on the right having large fillets. By measuring the angles of failure it was found that the shear angle of the small fillet specimen was —15° and of the large fillet specimen —18° from the cross-section plane of the shaft. The corresponding angles of the planes of maximum tension determined from the cast iron specimens were 35° and 31°. It is of interest that the difference between these angles of shear and tension are 50° and 49° and vary but 5° from the ideal value of 45°.

Fig. 11 Comparison of Fractures of a Ductile Material with those of a Brittle Material.

VIII. Plastic Flow Phenomena

The specimens tested were made from hot rolled and annealed SAE 1020 steel. The concentration values were the same whether the specimens were in the hot rolled or annealed condition, but the directional characteristics associated with the rolling process did seem to have an effect on the final plastic flow of the specimens. To explain this condition recourse was made to macro-structures and photoelastic analysis.

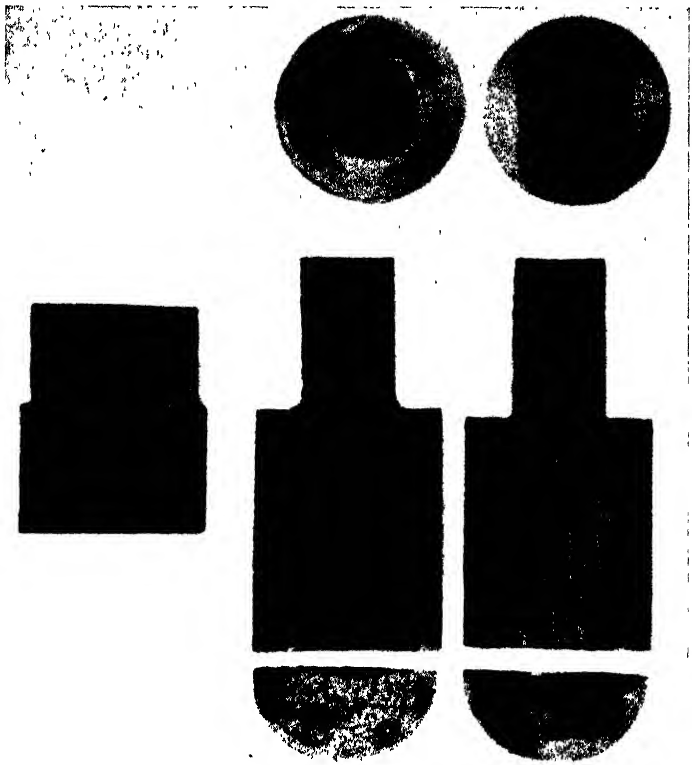
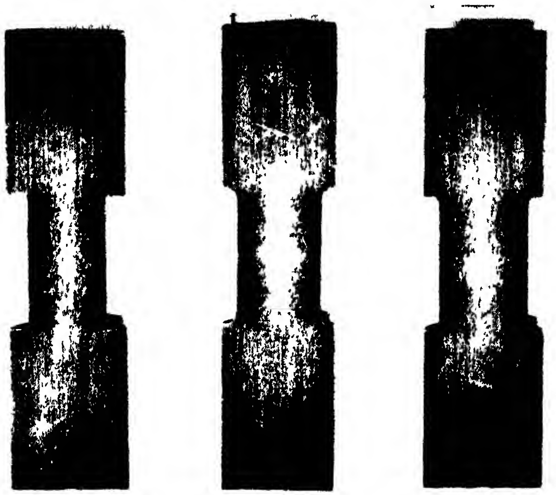


Fig. 12 Maco-structures of Specimens Subjected to Torsion.

MACRO-STRUCTURES. Strain patterns may be revealed by etching polished sections cut from severely deformed specimens. For the material used best results were secured using a mixed acid solution containing 38% hydrochloric, 13% sulphuric acid and 50% water. Immersing the specimen in the solution and heating gave the best results.

Fig. 12 gives macro-structures for hot rolled specimens. Fig. 12a gives a structure developed on a section cut through the center of a specimen having a ratio of large diameter to small diameter equal to 1.10. The concentration at the fillets is clearly revealed. Fig. 13b and 12c show the combined effect of the rolling process and the stress distribution at the end of the specimens due to the method of holding by four jaws in the chucks of the torsion machine. As the chuck in



(a) (b) (c)

Fig. 13 Maco-structures of Annealed Specimens Subjected to Torsion.

the machine revolves a twisting movement is transmitted to the specimen through the four jaws in the chuck with the result that very high stress concentrations occur in the neighborhood of the jaws. The mutual effect of these concentrated stresses gives a stress pattern very similar to a square on the cross-section of the shaft at the jaws. Outside this square the deformation is not sufficient for the etching reagent to be effective and near the center of the square, which is the center of the shaft, one would also expect the etching solution to be ineffective Although the center is not as dark as the corners, it does etch and this may be attributed to the part played by the fibering of the rod resulting from the rolling. By assuming the rod made up of a bundle of wires with their axis parallel to the axis of the rod, then the effect of the twisting on the small diameter would carry through and account for the high stress near the center of the cross-section. Evidence of this carrying through is given by Fig. 12d which gives the macro-structures for both ends, as well as for a section through the specimen. The jaw grips extended approximately one-third of the length of the section of large diameter. This picture 12d also shows the position of the stress concentration and the high stress along the

outside of the small diameter. Further evidence of the carrying through effect was obtained from macro-structures of sections cut from a rod of uniform diameter. In this case the square could be detected on a section removed at least three diameters from the jaws.

The specimens that had been annealed prior to the twisting showed no such structure when they were cut into sections and etched. In addition to the mixed acid solution, other reagents, such as an iodine solution, and Fry's reagent were tried without success in producing the fibred structure.[7] The annealing process consisted of heating the specimens for four hours at 1650° and allowing them to cool down with the furnace. This soaking of the steel above the critical temperature followed by slow cooling replaced the previous grain structure with a new equi-axed randomly orientated grain structure which had no directional characteristics. These specimens when etched showed the effects of stress concentration without the carrying through effects of the jaws.

Fig. 13 shows three specimens that were annealed, twisted, and then etched. Fig. 13a and 13b were twisted to failure while Fig. 14c was taken out of the machine before failure took place. Fig. 13a shows the effect of the small fillet and the high stress along the outer edge of the small diameter. The effect of severe stresses cannot be observed near the outside of the large diameters which is to be expected as the stresses vary inversely with the cube of the diameters and the difference in diameters is sufficient to keep the stress in the large part at a low value. Fig. 13b shows that the beginning of the fillet is the location of the maximum stress. Fig. 13c does not give the contrast the other specimens did, but does tell something about the place of maximum stress and general stress distribution.

PHOTO-ELASTIC PICTURES. To further verify the stress pattern on the cross-section of the twisted rods, photo-elastic pictures were taken of a circular disc subjected to approximately the same jaw loading conditions as the ends of shafts in their chucks. The photo-elastic analysis is confined to two dimensional stress conditions, but it is assumed that within the jaws the stress pattern would not vary much in the direction of the rod axis and as such may be assumed

[7] See Metallographic Testing for Ferrous and Non-Ferrous Metals; A.S.T.M., Designation E3-36.

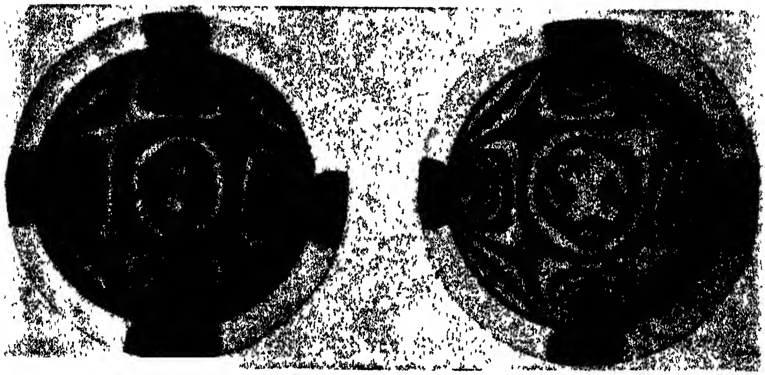


Fig. 14 Shear Stress Distribution in Circular Discs.

two dimensional. Fig. 14a and 14b give the shear stress pattern in a circular disc subjected to two different loading conditions. The pictures show the high stress concentration near the jaws and that these stress lines are approximately circular. The mutual effect of these concentration patterns on the rest of the specimen produces an approximate square similar to what was observed in the macro-etched specimens. The photo-elastic picture shows relatively low shear stresses near the center of the specimen which differs in degree from the macro-etched patterns. To explain the etching near the center of the rod the carrying through phenomena seem logical. A detailed analysis of the fringe patterns of Fig. 14a and 14b would show that the point of maximum shear stress is not at the contact of the disc and the jaws, but underneath the jaws at a distance inside the rim of the disc.[8] This explains why the corners of the squares in the macro-etched specimens do not occur at the outer edge of the shaft. The fact that the corners of the square are displaced slightly from the position of the jaws is due to the difference in loading of the actual shaft in the machine as compared to the ideal conditions assumed in loading the transparent disc. The jaws of the machine apply their load at an angle to the radial lines of the shaft which accounts for the displacement.

IX. Comparison of Results with Published Data

The various methods used for the determination of torsional stress

[8] See—Horger, O. J. "Photo-Elastic Analysis Practically Applied to Design Problems"; Jr. of Applied Physics, July, 1938, p. 461.

concentrations appear to yield results which are not in agreement with one another. These methods may be classified as the mathematical method of Willers[8], the electrical analogy of Jacobsen[9], the brittle material method as used by Seely and Dolan[10], and the reversed stress method as used by a number of investigators.[11] [12]

A comparison of concentration values obtained by the plastic flow method as compared to those of Jacobsen are given in Fig. 15. The curves show the values corresponding to the low and high values of the diameter ratios to agree quite well. The distribution of the curves bearing diameter ratios of 1.2, 133 and 1.5 between the limits 1.1 and 2.0 do not agree so well.

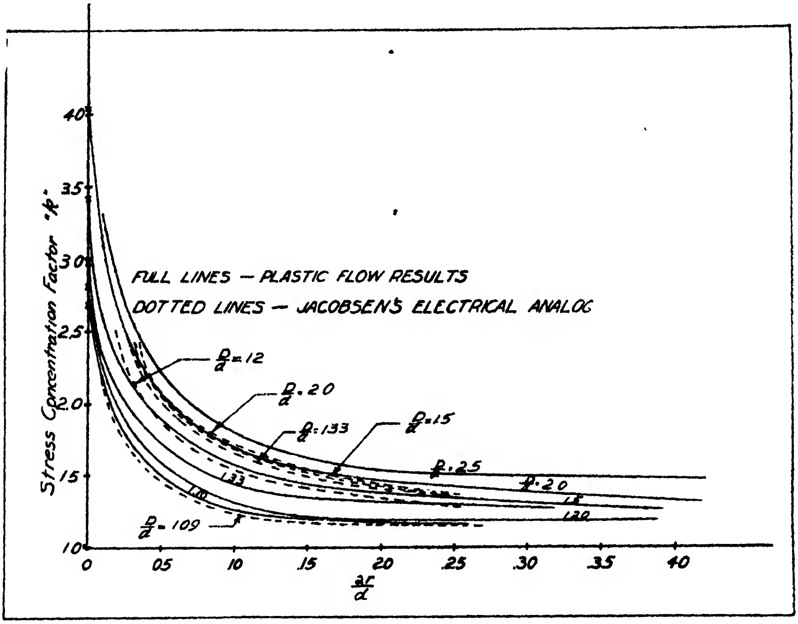


Fig. 15 Plastic Flow Results Compared with those of Jacobsen.

[9] Jacobson, L. S. "Torsional Stress Concentration in Shafts," A.S.M.E. Trans., 1925, Vol. 47, p 619.

[10] Seely, F. B. and Dolan, T. J. "Stress Concentration at Fillets, Holes and Keyways as Found by the Plaster-Model Method"; Bulletin 276, Eng. Exp. Station, Univ. of Illinois, June, 1935.

[11] Dolan, T. J. "The Combined Effect of Corrosion and Stress Concentration at Holes and Fillets in Steel Specimens Subjected to Reverse Torsional Stress"; Bulletin 293, Eng. Exp. Sta., Univ. of Illinois, April 1937.

[12] Armbruster, E. "Einfluss der Oberflachenbeschaffenheit auf den Ing. Spannungsverlauf und die Schwingungsfestigkeit" Ver Deutsch Ingr. Verlag, 1931.

The results of tests using plaster models[11] showed very low concentration effects associated with the fillets. Using a square corner with a value of large diameter to small diameter equal to two, the stress concentration factor equaled 1.30 and for a value of 2r/d equal to 0.12 for the same size of shafts the average value of "k" was equal to 1.13. These values seem very low and hard to explain although the results of fatigue or repeated stress on certain materials give values equally low.

The concentration factors obtained from repeated stress tests give results that vary considerably with the material used. There is so much variation that it can only be said that for a particular material of specific dimensions a particular value of "k" was determined by means of the reversed stress method. It does not necessarily follow that the concentration values obtained by the reversed stress method should equal those obtained by the plastic flow method. The latter method uses the change in yielding characteristics as an index of concentration while study has shown that there is no reliable one to one correspondence between the yield strengths and endurance limits of materials It is of interest to point out that the values obtained by the plastic flow method are higher than those obtained for either the brittle material method or the reversed stress method, so that they can could be used with safety. They must, however, be confined to torsional cases as the stress concentrations produced in bending of shafts of the same geometrical proportions are considerably higher.[18]

ACKNOWLEGEMENTS

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The writer is also indebted to Mr. Ivan Shirk and Mr. Arthur Baker of the Department of Mechanical Engineering for their help with the test work.

[18] Peterson, R. E. and Wahl, A. M. "Two and Three-Dimensional Cases of Stress Concentration, and Comparisons with Fatigue Tests"; Journal of Applied Mechanics, A.S.M.E., Volume 3, March, 1936.

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Vol. XXII November, 1939 Number 6

Physical Properties of Magnesium Alloys:
No. 4—Heat Treatment of Magnesium Alloy Containing Zinc and Aluminum

by James G. McGivern
Lately Assistant Professor of Mechanical Engineering

Progress in Photoelasticity

by Royal Weller
Instructor in Mechanical Engineering

ENGINEERING BULLETIN NO. 60
ENGINEERING EXPERIMENT STATION
H. V. Carpenter, Director

PUBLISHED BY THE STATE COLLEGE OF WASHINGTON

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

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Heat Treatment Of A Magnesium Alloy Containing Zinc And Aluminum

James G. McGivern
Lately Assistant Professor in Mechanical Engineering

I. INTRODUCTION

The many studies made on the equilibrium relations between magnesium and other elements have established a rational basis for a study of the heat treating possibilities of magnesium alloys. The equilibrium diagrams obtained from these studies indicate that alloys of magnesium containing aluminum, bismuth, calcium, cerium, lithium, manganese, lead, silver, tin, zinc, or thallium all show a decreasing solubility with a falling temperature and as such are capable of age hardening[1]

When using this as a basis of heat treatment the resulting changes in hardness vary considerably, depending upon the particular alloying element, the rate at which its solubility decreases with temperature, and the ease and manner with which the excess constituent goes out of solution. In some instances, although the diagrams predict aging possibilities, the actual hardness changes are very slight and at the present time these alloys are of little commercial importance. Others such as alloys containing aluminum give considerable change with heat treatment and have been in commercial use for some time. Alloys with zinc also exhibit hardness changes upon heat treatment and as a material of engineering they are just coming into use, although actual data on their specific properties resulting from heat treatment are lacking in the literature.

The purpose of this paper is to present the results of heat treatment on the tensile properties of an extruded magnesium alloy containing 3% zinc and 3% aluminum. The heat treatments consist of annealings at relatively high temperatures and two aging treatments, one from the as-received condition and the other from the annealed state. For each individual treatment curves are plotted

[1] Chubb, W. F., "Age Hardening Magnesium Alloys." Light Metals, April, 1939

for the usual values of hardness, maximum strength, breaking strength yield strength (.20% permanent set) percentage elongation in two inches and reduction in area. In addition the yield strength (.10% permanent set) Johnson's limit, stresses corresponding to specified sets, true elongation in two inches, and the true breaking stress on the basis of the reduced diameter are given. These values are included to furnish data to later correlate with the results of shear tests now being planned.

II. HEAT TREATMENTS

The heat treatments given this alloy prior to testing are described in detail in the preceding bulletins of this series.[2,3,4] These treatments are all based upon the decreasing solubility of the alloying element in magnesium accompanying a lowering of temperature. As in preceding experiments the specimens were covered with iron filings to prevent oxidation.

The annealing treatment consists of heating at temperatures above 600°F. This is above the line in the equilibrium diagram indicating the limit of solid solubility of zinc in magnesium.[5] This treatment has two objectives, the first to relieve the material of any strain hardening associated with the extrusion process and secondly to cause any undissolved inter-metallic compound to go back into solution. To relieve the cold working effects recrystallization must take place. The zinc and aluminum will raise the recrystallization temperature of the alloy but it is doubtful if it will raise it 298°F. above the quoted temperature of 302° F. for pure magnesium.[6] The amount of precipitated intermetallic compound that must go back into solution as such, or as the individual metals, is a function of the degree of working and the temperature at which the working was done. This varied considerably among the specimens as evidenced by the micro-structures.

[2] McGivern, James G., and Wilkinson, Clinton A., "Precipitation Hardening of a Magnesium Alloy Containing Aluminum," Eng. Exp. St. Bulletin No. 50, 1937.

[3] McGivern, James G., "Physical Changes Accompanying High Temperature Annealing of a Magnesium Alloy," Eng. Exp. Sta. Bulletin No. 52, Jan., 1938.

[4] McGivern, James G., "Physical Changes Accompanying the Aging of a Magnesium Alloy," Eng. Exp. Station Bulletin No. 54, September, 1938.

[5] Chadwick, "Constitution of the Alloys of Magnesium and Zinc.," Jr. of Ind. of Metals, 1928, Vol. 39.

[6] Jefferies, Z. and Archer, R. S., "Science of Metals," Mc-Graw Hill Book Company, New York, p. 86, 1924.

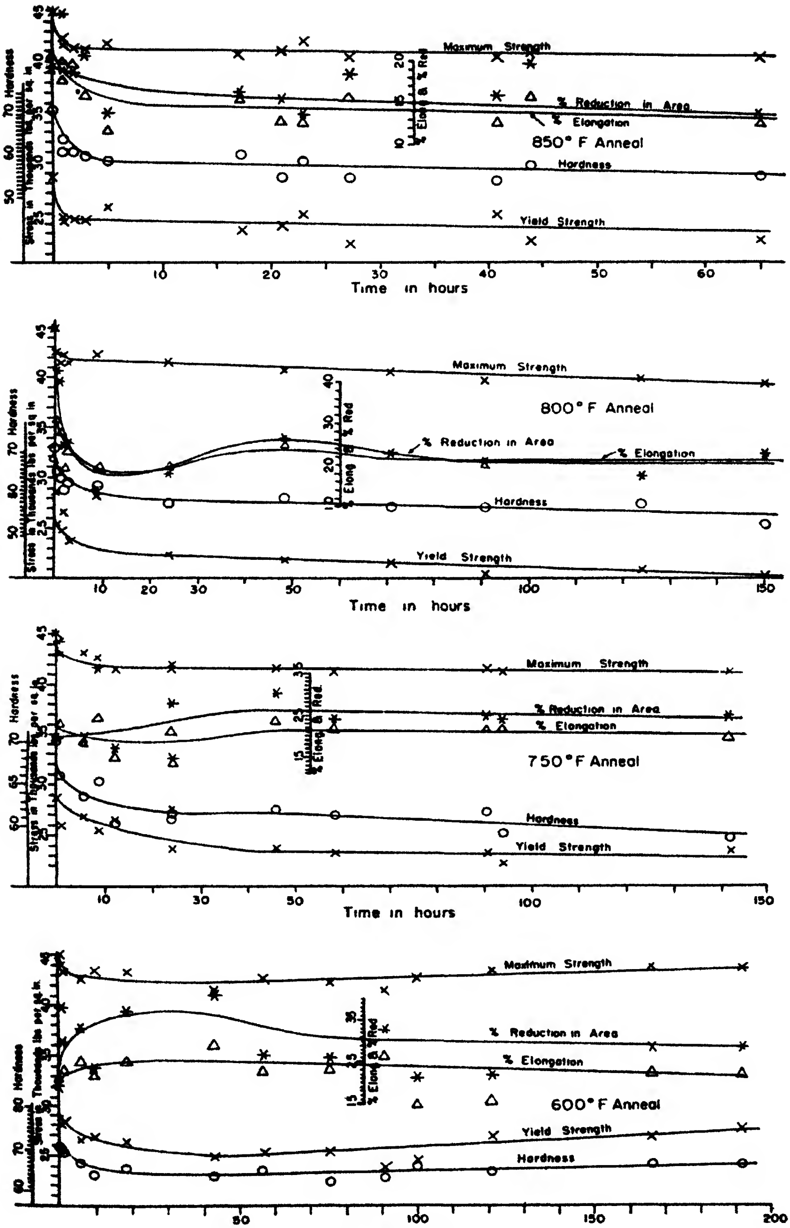

Fig. 1. Changes in Physical Properties Accompanying Annealing.

The aging treatments consist of heating the material at temperatures up to 420°F. This was done to material in the as-received condition and to specimens that had previously been annealed at 800°F. After specified lengths of time specimens were taken from the furnace, quenched in water and then tested for hardness and strength.

III. ANNEALING TREATMENTS

Figure I gives the changes in physical properties for 850° F., 800°F., 750°F. and 600°F. annealing treatments. The 850°F. anneal gives the lowest strength and ductility characteristics and these remain practically constant after the first four hours. For the other curves the change in properties remain practically constant after a period between twenty-five and fifty hours. The changes in the first stages are associated with the recrystallization following the extrusion process and with the obtaining of an equilibrium condition with respect to the previously precipitated intermetallic compound. Before heating the working effects and precipitation both contributed to giving the material directional characteristics.

The working process being above the critical working temperature caused the hexagonal crystal lattice of the magnesium metal to line up with the basal planes parallel to the direction of working. Since a hexagonal crystal has only one plane of easy slip this preferred orientation leaves the alloy with very definite directional properties. To further accentuate this condition the precipitation of the intermetallic compound occurred in stringer form in the direction of working as seen in figure 2a. The annealing caused the precipitate to rearrange itself as illustrated by the micro-structural changes accompanying 800°F. annealing given in figure 2. Experiments have shown that recrystallized grains resulting from annealing do not always have random orientations but that for magnesium the recrystallized grains many times have the same directional properties as the originally worked metal.[7] Experiments are now being conducted on this characteristic and present indications are that this alloy retains its directional characteristics upon annealing.

[7] Schiebold, E., & Siebel, G., "Zeitschrift fur Physik," Vol. 69, p. 458.

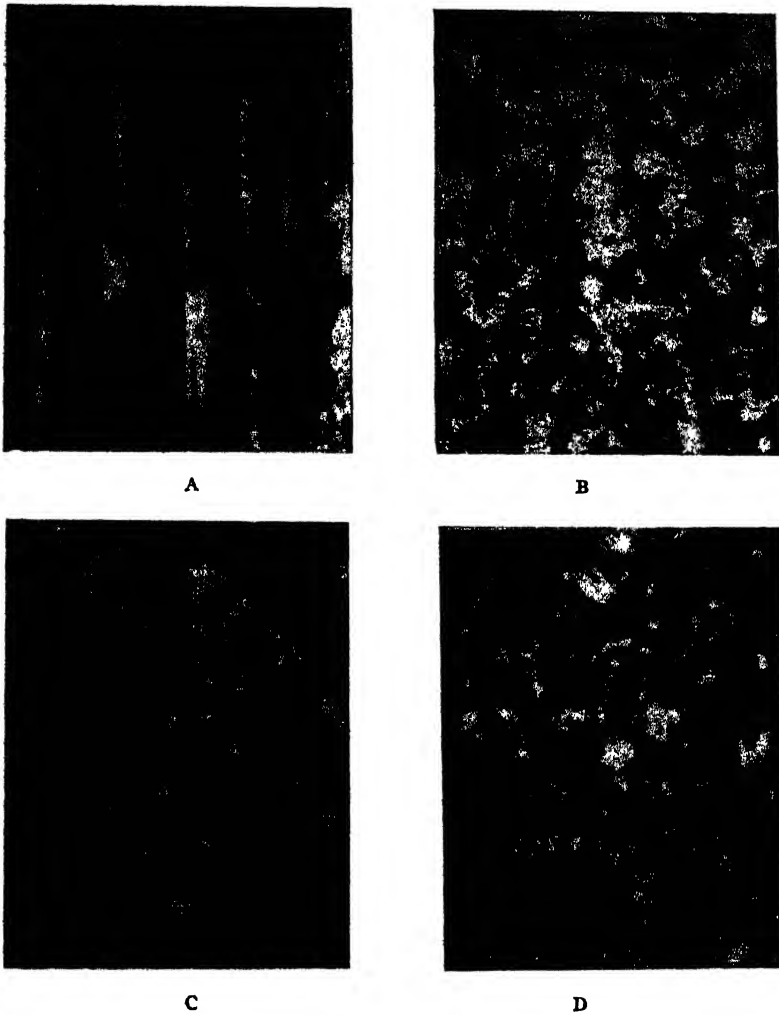

Fig. 2. Changes in Micro-Structures for 800°F. Annealing. Specimen A untreated. B, C, and D have been annealed 3½, 6 and 22 hours respectively.

The original material varied as revealed by hardness and the amount of precipitate observable on micro-structures. The breakdown of the fibered structural pattern is illustrated by figure 2. At the end of three and one-half hours the stringers have been broken up

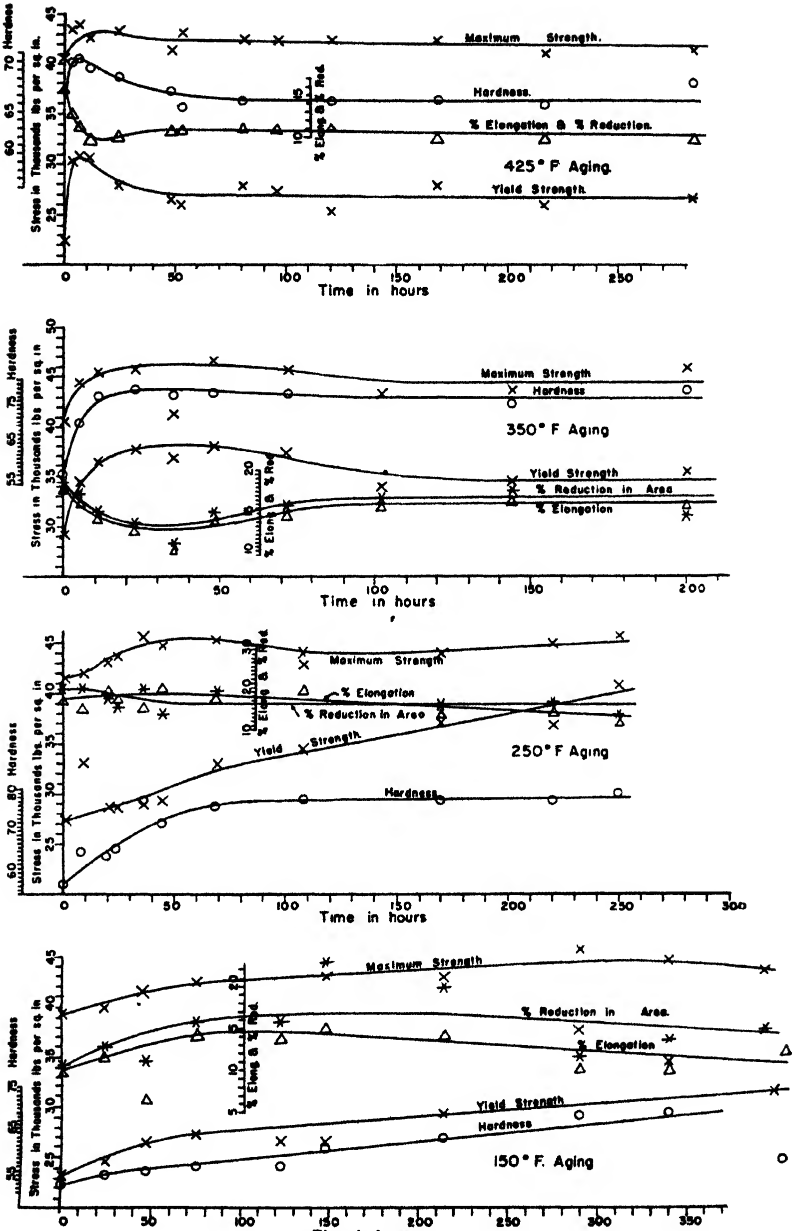

Fig. 3. Physical Properties Accompanying Aging Following Annealing

and with further heating a more uniform dispersion is revealed. Considerable difficulty was experienced in securing a satisfactory etch for this alloy. After trying many solutions it was found that a strong solution of malic acid would reveal precipitation while strong solutions of H_2SO_4 and NOH_3 would bring out grain boundaries. To draw any worthwhile conclusions as to the mechanism of precipitation or of the dissolving of the inter-metallic compound more work should be done. Particular consideration should be given to the ability of an inter-metallic compound to form solid solutions which seems to be open to question.[8]

IV. AGING FOLLOWING ANNEALING

Figure 3 gives the results of aging following a preliminary 800°F. anneal. The aging temperatures used were 420°F., 350°F., 250°F. and 150°F. The object of these tests was to determine the effect of temperature on rate and amount of precipitation from the supersaturated solid solution that was produced by quenching from 800°F. The effect is measured by change in physical properties accompanying the aging process.

The increase in the slope of the hardness, yield strength, and maximum strength curves with increasing temperatures as given in figure 3 show that the rate increases with temperature.

Although the rate of aging is faster the maximum strength and hardness of the 420°F. aging is not as great as for the lower 350°F. aging. This may be accounted for by the fact that at the higher temperature the solubility of the zinc in the magnesium increases which decreases the amount of super-saturation of the inter-metallic compound. Both the 420°F. and 350°F. curves show overaging. This may be attributed to the fact that the precipitated particles are larger than that required to produce maximum hardness.[9] Because of the visible precipitate at the beginning of aging it is not probable that overaging in this case is explained by the Knot theory[10] which attributes hardness to the atomic forces set up in the formation of the inter-metallic compound which is followed by

[8] Gann, J. A. and Brooks, M. E., "Constitution of Magnesium Zinc Alloys," Metals Handbook, 1939 edition.
[9] Merica, P. D., Waltenberg, R. G. and Scott, H., "Heat Treatment of Duralumin," Bulletin American Institute of Mining Engineering, page 973, June, 1919.
[10] Merica, P. D., Transactions of A.I.M.E. (1932).

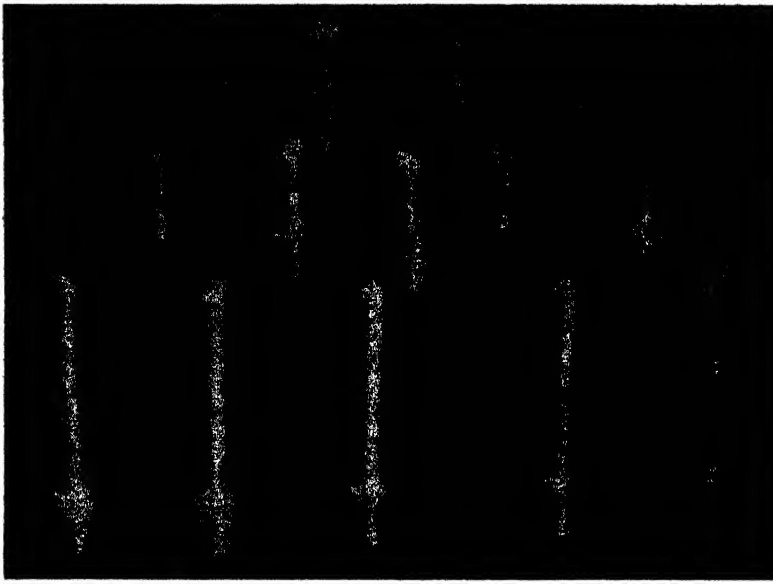

Fig. 4. Fractured Specimens. (Reading from left to right). Specimens in top row have been aged at 350°F. 103 hrs., 0 hrs., 200 hrs., and 5 hrs., respectively following a preliminary 800°F. anneal for 18 hrs. Second row has been annealed at 800°F. 3 hrs., 24 hrs., 9 hrs., 1½ hrs., and 0 hrs., respectively. Bottom row has been aged at 360°F. from extruded condition 5 hrs., 233 hrs., 17 hrs., and 35 hrs., respectively.

a softening or overaging when the particles are actually formed and precipitated. The actual changes in strength resulting from aging are not as great as those previously reported for the magnesium alloy containing 8% aluminum and the ductility is not enough different to offset the lower strength.

The results given in figure 3 are typical values obtained when the aging followed heating an arbitrary number (17½ and 18½) of hours at 800°F. Although complete tests on all the physical properties were not taken hardness tests were made on specimens aged after being annealed for different lengths of time at various annealing temperatures. The results of these tests were similar to those reported, any differences being due to rate of aging rather than final values obtained.

The types of fracture accompanying the 800°F anneal and the 360°F aging are given in figure 4. These specimens show how the type of fracture changes gradually from the 45° shear failure of the speciment to the square type of brittle tension failure for the completely aged specimen.

V. AGING FROM THE EXTRUDED CONDITION

Figure 5 gives the physical properties of specimens aged at 420°F, 360°F, and 250°F from the extruded or as-received condition. In the first five to ten hours of heating these curves show that the yield strength, hardness and maximum strength drop. After this initial softening which is attributed to a particular anneal the strength and hardness increase until they reach a value which apparently is a maximum for each treatment. The accompanying change in elongation and reduction of area is not so apparent but is pronounced for the 360°F treatment. It will be noticed that the change in the yield strength is greater than the corresponding changes in the maximum strength. The low temperature, (250°) aging appears to give desirable results. The maximum strength varies very little but the yield strength increases to 34,000 lbs/sq. in. from 28,000 lbs/sq. in. This change is not done at a sacrifice of ductility as the data show that both the percentage elongation in length and percentage reduction in area are above 20%.

Figure 4 gives fracture pictures accompanying the 360°F aging and these show the transition from the shear fracture to a combination shear and tension fracture which accompanied the aging.

VI. EFECT OF TEMPERATURE ON HEAT TREATMENT

All of the preceding charts give changes in physical properties accompanying heating for various time intervals. By taking the same data and using temperature as a variable, charts similar to figure 6 are obtained. These curves are correct for a fifty hour heat treatment but are typical of those obtained using different heating times.

Figure 6 may be divided roughly into four different sections. The first section represents a condition indicating little aging effect. This division has as its upper limit approximately 175°F. For charts based

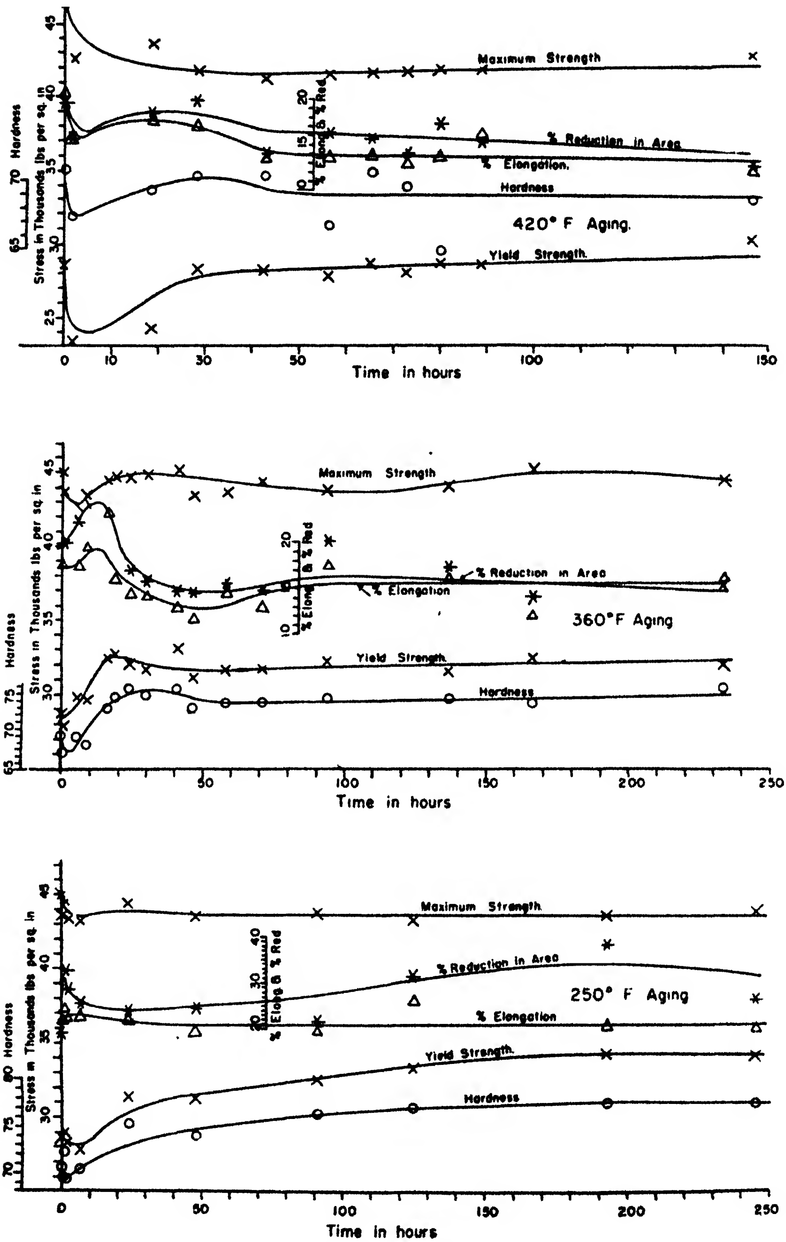

Fig. 5. Aging from the Extruded Condition.

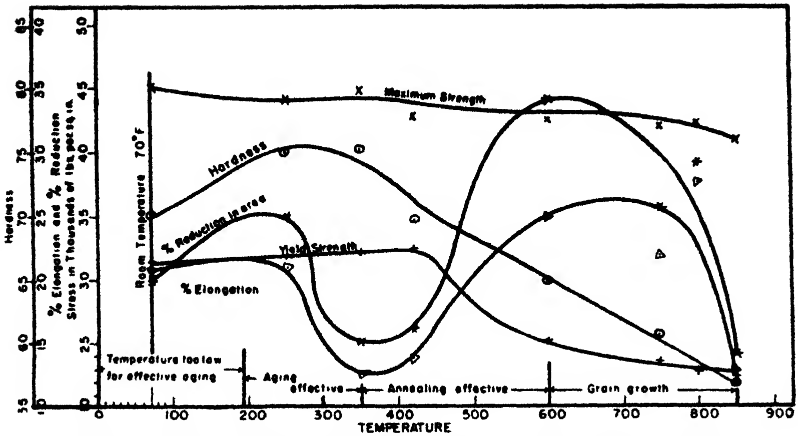

Fig. 6. Effect of Temperature on Specimens Heat Treated 50 Hrs.

on shorter heating times the upper temperature of this region would increase while for heating times more than fifty hours the temperature would be less. This upper limit of ineffective aging varies from approximately 125°F. for 150 hour heating up to 200°F. for 25 hour heat time. The second section may be associated with effective aging and is accompanied by an increasing hardness and decreasing ductility. For figure 6 this section has a lower and upper temperature limit of approximately 175°F. and 360°F. respectively. The third section gives the lower and upper temperature limits for effective annealing. Above the upper limit of effective annealing the ductility decreases without an accompanying increase in hardness and strength. This gives ineffective annealing and is caused by grain growth.

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Progress In Photoelasticity

Royal Weller
Instructor in Mechanical Engineering

In 1815 Sir David Brewster discovered that glass under stress exhibited colored patterns when viewed between polarizers. Since then the photo-elastic method, so called, has been of steadily increasing usefulness to the engineer. In brief the method is as follows. When one desires to discover the stress system existing within a loaded machine or structural part, for which other methods of analysis are difficult or impossible, he makes a model of this part from some transparent material. This model is loaded to simulate the conditions of service in the actual part. It is then placed between two devices for polarizing light. The stress system within the model becomes visible as bands of color, and analysis of the position and intensity of these bands will enable the observer to determine the characteristics of the stress system.

In the early days of the photoelastic method it suffered from lack of suitable equipment for polarizing light, lack of a suitable material from which to make the model, and from inadequacy in the theories which concerned optical phenomena. The deficiencies have now to a large extent been remedied so that at present it is possible to make stress analyses with ease and accuracy.

The development of material for these investigations did not take place until about the year 1930. This material is Bakelite, one of the modern plastics or synthetic resins. Previous to 1930 celluloid was commonly used and before that experimenters relied on glass. The former was rather insensitive and the latter both insensitive and difficult to fabricate. Bakelite is optically quite sensitive, its elastic properties are good, and it is easy to cut into models of complex shape. Of the various materials which are classified under the name of bakelite the particular type known by the specification number BT-61-893 seems to be most adapted to model making.

Early experimenters were troubled by the fact that the stress patterns obtained in these experiments were dependent not only on the

load placed upon the model but also on the position of the model with respect to the devices used for polarizing the light. This was remedied by the use of circularly instead of plane polarized light. The invention of the quarter-wave plate by Clerk Maxwell made this step possible. A more recent development has been the substitution of monochromatic light for the white light previously used with increased accuracy in results.

The theory of photoelasticity so far as it relates to engineering practice has been steadily developed over the past century. Now it is a simple matter to compute the stress system within a model from the data obtained in a photoelastic polariscope, the device which includes the optical and mechanical equipment for loading the model and observing the resulting patterns. There is still work to be done, however, on the question of the basic reason for the photoelastic effect. It should be possible, for example, to predict from the molecular and atomic structure of a particular material as to whether it will make a suitable medium for photoelastic models. At present this cannot be done. The investigation of the suitability of materials must still be largely a question of blind experiment. This does not concern the engineer who desires results in connection with design, but only the physicist or chemist who would like to know more about the fundamental nature of the materials with which he deals. And since such a satisfactory material as bakelite is already available the study of this problem is now of less importance than it was a few years ago.

At present many educational institutions (including Washington State College) and industrial concerns are equipped to perform this type of stress analysis. A wide variety of problems have been solved. These include the study of stress concentrations around holes and fillets, stresses in gear teeth, dovetail joints, distribution of load in indeterminate structures, and countless others. The automotive and electrical industries, the railroads, as well as several branches of the governmental research organizations are using the method freely.

The most common type of equipment for photoelastic analysis consists of a loading frame in which the models are placed, an optical system by means of which a beam of polarized light is passed through the loaded piece, and a camera with which the resulting patterns are recorded. With such apparatus one may easily and quickly determine

the points at which concentrations of stress take place, measure the stress with an accuracy of about 3% and thus determine changes in design which will render the machine or structure stronger or stiffer, or which will enable the designer to remove material where the stresses are low and thus save weight. A proper utilization of the results of such an analysis enables one to arrive at the most efficient design far more rapidly than by other methods.

In the past the usefulness of this type of stress study has been limited to cases of plane stress, that is, to shapes which could be cut of a sheet of uniform thickness. This permits one to examine the stress in an ordinary gear tooth, for example, since such a tooth is plane on both sides and the load lies parallel to these planes. A shape such as a crankshaft, however, could not be treated since it is not bounded by parallel plane surfaces on two opposite faces.

In 1938 Opel in Germany announced a method by which three-dimensional stress systems (such as the crankshaft) could be treated photoelastically. His method involved heating the model to a temperature of about 250°F. and loading it at that temperature. The model was then cooled back to room temperature with the load still applied. After cooling the load was removed and it was found that the model exhibited a stress pattern which was characteristic of the load, even though it was no longer acting. The model was then sliced into two-dimensional plates and these plates examined in the usual way. This method possesses several disadvantages. The optical and elastic properties of the model are altered by the heat treatment. The model is destroyed by the slicing process and cannot be reloaded nor examined while the load is being applied. There is danger of disturbing the pattern by the slicing process. And finally, the deformations which take place at the elevated temperature and which are preserved after cooling are so great that the model is no longer of its original shape.

In the course of recent experiments the writer discovered that the problem of three-dimensional analysis could be much simplified by making use of the fact that the process of scattering light will polarize it. In this method a beam of polarized light is passed through a slit and then into the model which may be any shape whatever. The light illuminates a plane section through the model and any section desired may be so illuminated. When such a section is viewed from the proper

direction a pattern appears within the model which is characteristic of the stress system in the illuminated plane. By surveying various planes through the piece the entire stress system may be found.

The photoelastic method has thus come from a laboratory toy to a powerful tool for stress analysis which may be applied to any shape whatever with the expectation of discovering the way in which such a shape reacts to external loads. In many cases of practical interest the more conventional methods of attack are either partially or completely unable to deal with complex shapes and the photoelastic procedure offers the only solution except to cut and try. And even in certain cases where other methods are useful it frequently happens that the optical procedure here outlined will be speedier and more accurate.

In addition to the conventional type of photoelastic study, a program of research is being set up at the State College of Washington for the purpose of furthering the work in three-dimnsional procedure. A new type of polariscope is now under construction and will be in service in the early part of 1940. Experiments dealing with the applications of optical methods to the flow of fluids will be conducted in addition to the more conventional treatment of the stresses in solid bodies. This will be one of very few places in which three-dimensional methods will be employed inasmuch as the new technique was announced but four months ago

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Directional Properties of Worked Magnesium Alloys

by James G. McGivern

Lately Assistant Professor of Mechanical Engineering

Some Geologic Aspects of the Magnesite Deposits of Washington

by H. E. Culver

Head, Department of Geology

ENGINEERING BULLETIN No. 61

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

PUBLISHED BY THE STATE COLLEGE OF WASHINGTON

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The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

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Directional Properties of Worked Magnesium Alloys

James G. McGivern
Lately Assistant Professor of Mechanical Engineering

I. INTRODUCTION

Commercial metals are considered isotropic even though the crystals that make up the metals possess directional properties. This assumption is justified because the axes of the equiaxed grains have random orientations in most polycrystaline materials. The slip planes of one of these grains is not in line with those of adjacent grains and the metal as a whole is considered isotropic. There are conditions however when metals have very decided directional properties and unless allowance is made unpredictable failures may take place. These directional properties may be due to casting conditions causing dendritic or columnar formations, to working processes causing a fibering, to working followed by annealing causing abnormal grain growth, and to an orientation of all grains in a common direction due to working.

Most ingots are provided with round corners to prevent breaking in rolling or forging due to columnar grains at sharp corners. Cases of fibering are common and result when metals containing impurities or two phases of different hardnesses are rolled, drawn, extruded, pressed or forged. The process of working followed by annealing has been rather thoroughly investigated and has been used to produce large single crystals.[1] For making a single crystal wire of tungsten for use in incandescent lamps a polycrystalline wire made from compressed and consolidated tungsten powder is drawn through a furnace at a critical rate. Practically all metals exhibit the effects of a preferred crystal orientation resulting from the working process. However, severe directional properties are restricted to the group of metals having hexagonal crystal lattices which includes magnesium, zinc, beryllium and cadmium. Beryllium and cadmium at the present time are used as alloying elements only, and zinc recrystallizes at as low a temperature as 70° F. after it has been worked. This means that of all

[1] **Carpenter, H. C. H. and Elam, C. F., Proc. of Royal Soc., 1921**

commercial metals magnesium would be expected to have the most decided directional properties following work done below its recrystallization temperature.

It is the purpose of this bulletin to present the results of experiments made to determine the extent of these directional properties in some extruded magnesium alloys. Tests of the metal in the condition as received and also following recrystallization are considered. In addition to the test data the mechanism of crystal deformation is reviewed, the technique of testing described and typical curves and fracture pictures are included.

II. MECHANISM OF CRYSTAL DEFORMATION

Figure 1 illustrates the structural units of the three principal types of crystal lattices possessed by the majority of the common metals.

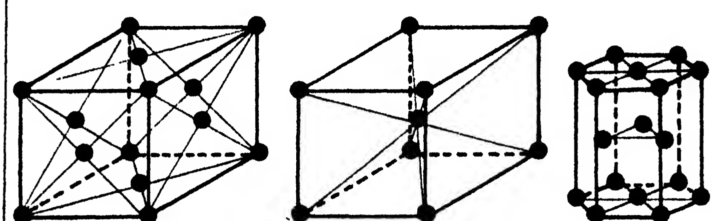


Fig. 1. Typical Crystal Structure.

These are the face centered cubic, the body centered cubic and the hexagonal type of lattices. It is noticed that the planes of greatest atomic density vary for the various structural forms. For the face centered cubic these planes are the faces of the cube while for the body centered lattice they are diagonal planes containing the corner atoms and the center atom. The atomic density is not as great for the body centered cube as the diagonal plane is larger than the side of the cube. The hexagonal lattice has only one set of planes of maximum atomic density which are the so-called basal planes and are the top and bottom planes of the hexagon given in Figure 1. These planes are of real

significance in explaining the workability of metals as the slip planes in crystals are parallel to the planes of maximum atomic density. This helps to explain why the materials having face centered cubic lattic structures, represented by copper, gold, silver, gamma iron, aluminum and nickel, are so highly ductile. The less ductile metals such as alpha iron, chromium, tungsten and vanadium have body centered cubic lattices. This crystal theory also helps to account for how a hexagonal metal such as magnesium may be ductile if its crystals are oriented in one direction and very brittle if oriented in another direction.

When magnesium is extruded through a die or rolled each individual crystal within the metal is oriented during the working process so that the metal deforms with the least amount of energy. Upon the completion of the work the crystals remain with their basal planes in the direction of the original working and as such have many of the characteristics of a single crystal In this condition they resemble a pack of cards and if shear force is applied parallel to their basal planes they will deform under relatively low loads. If compressed at right angles or parallel to their basal planes there will be no shear component acting on the basal planes and relatively less deformation will take place. Since the maximum shear resulting from compression acts on a plane making 45° with the compression plane it follows that for easy slip to occur the compression stress should be applied to a plane making 45° with the basal planes.

III. EXPERIMENTAL METHOD

Cubes .580″ on a side were cut from one inch diameter extruded rods of magnesium alloys. The alloys tested contained 6% Al, 8% Al, and 3% Al, with 3% Zn, the remainder of the alloys being magnesium with the exception of a slight amount of manganese. These cubes were cut in sets of twelve similar to the half set indicated in Figure 2. By compressing these cubes across their faces it was possible to obtain changes in physical properties for angular increments of 15°. To

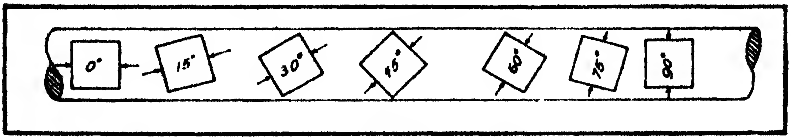
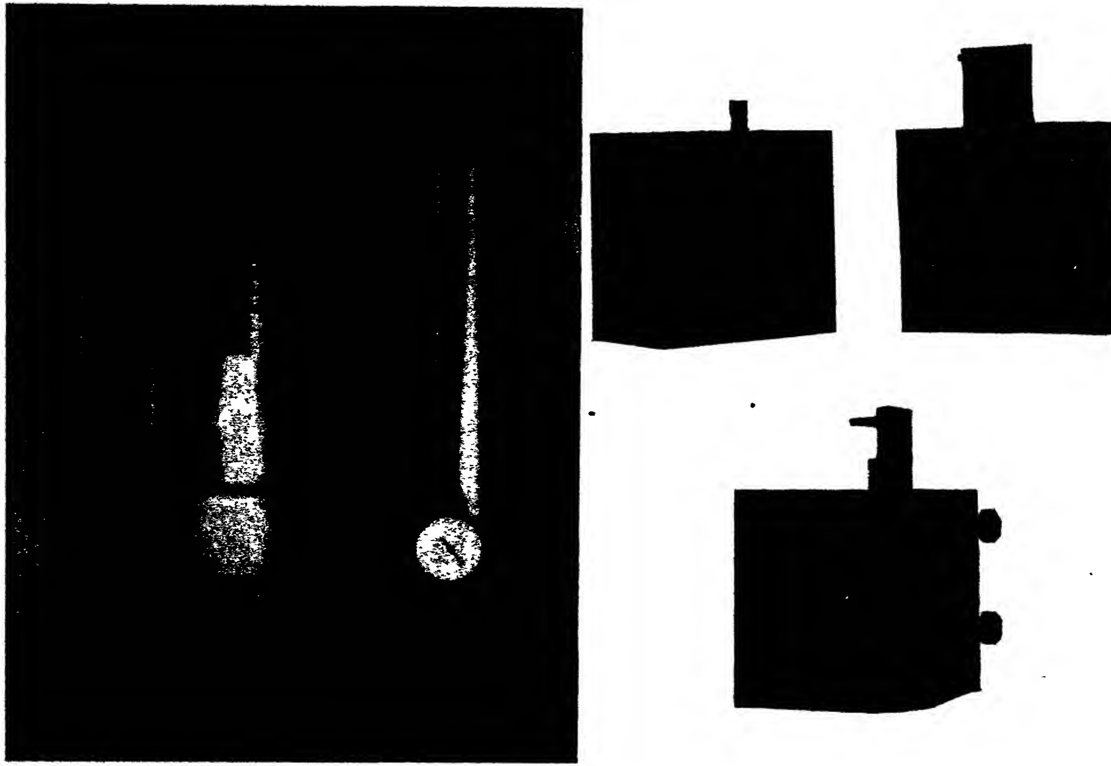


Fig. 2.



A B

Fig. 8. Experimental Set Up and Shear Block.

insure sufficient accuracy the set-up illustrated in Figure 3 was used. The cubes were placed between the surface hardened blocks and the compression deformations were magnified by use of levers. The dial micrometers were read to one-fifth of a thousandth of an inch and readings were taken at intervals of approximately 750 lbs. per square inch. The loads were applied slowly and uniformly to all specimens and cubes were tested in the "as received," in the annealed and in the aged condition.

In order to correlate the compression values with those obtained from pure shear, cubes were tested in the especially designed shear block illustrated in Figure 3b.

TYPICAL RESULTS (Results of Compression Tests)

Figure 4 shows a representative set of stress strain diagrams obtained from compression tests on cubes cut from a magnesium alloy containing 8% aluminum. The compression angle as measured from the axis of the rod is given for each curve. These results show clearly

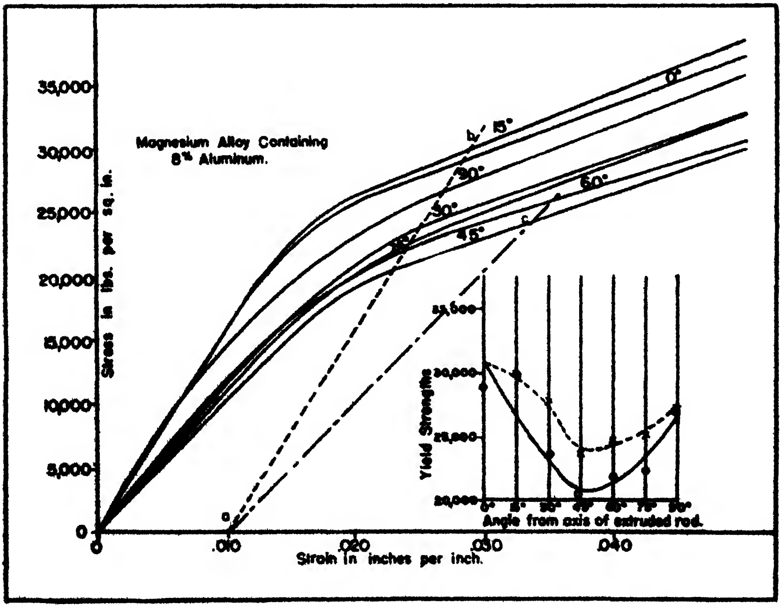


Fig. 4. Typical Curves Illustrating the Directional Properties of a Magnesium Alloy.

the directional characteristics of this material as indicated by the effect of angle of compression on the slope of the modulus line and on the yielding characteristics. To evaluate the yield strength two methods were used. The first and simplest method consisted of drawing the line ab parallel to the highest modulus line and reading off the stresses corresponding to where this line intercepted the various stress strain curves. These values are plotted for the various compression angles and represented by the full line in the lower right-hand corner of Figure 4. The other method consisted in taking the line from "a" parallel to the modulus line of the curve for which the yield strength was to be determined. This is illustrated by taking line ac parallel to the modulus line of the 45° curve and determining the stress at "c" corresponding to the interception of the line ac and the 45° stress strain curve. By following the same procedure for the other stress strain diagrams the yield strengths represented by the dotted line of the figure were obtained. The first method is the simplest and will be used in this bulletin.

It will be noticed that the yield strength for compression at 90° with the extrusion axis is not as great as it is with the compression in line with the axis of the rod. There are two reasons for this—one connected with the direction of the basal planes and the other associated with the inclusion stringers in the metal.

The rods used were circular in cross-section so that the basal planes of the hexagonal lattice although parallel to the rod axis arrange themselves circularly around the rod. By compressing the cubes cut from the rod in a direction perpendicular to the rod axis some of the basal planes are favorably oriented and the diagonal shear stress will be effective. This means the plane of failure for the 90° compression should be normal to the cross sectional plane of the shaft. This proved to be the case and the fractures for these specimens differed from those obtained when compression was parallel to the shaft axis.

The directional properties due to stringers within the metal are explained by reference to Figure 5. This figure shows micro-structures of a magnesium alloy containing 8% aluminum in the "as received" condition. This material is capable of aging,[2-3] and the amount

[2] McGivern, J. G., "Precipitation Hardening of a Magnesium Alloy Containing Aluminum," Eng. Exp. Sta. Bulletin No. 50, July, 1937.

[3] McGivern, J. G., "Physical Changes Accompanying the Aging of a Magnesium Alloy," Eng. Exp. Sta. Bulletin No. 54, Sept., 1938.

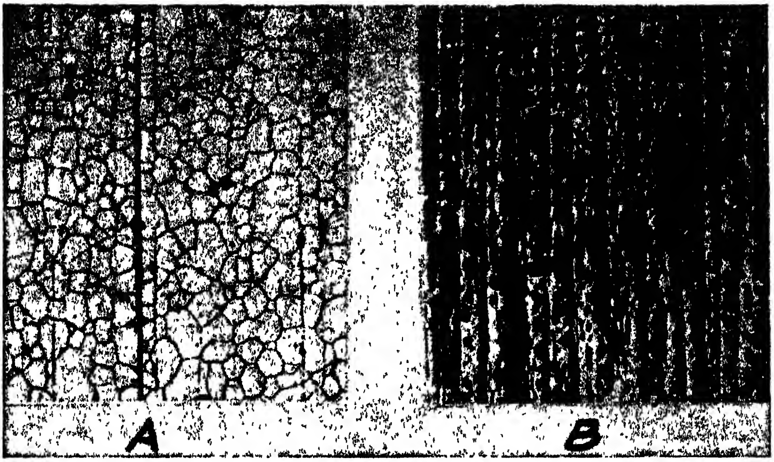


Fig. 5 Difference in micro-structures of rods having different initial hardnesses. Specimen A (65 Rockwell E) and B (69-71 Rockwell E) 100X.

of visible precipitation varies for different rods as shown in Figure 5. The precipitation in the form of stringers causes the material to behave similar to a bundle of individual wires which would be relatively weak when compressed perpendicular to the axis.

Figure 6 gives results of compression tests on three different alloys in the "as received" condition. The individual values show that specimens of the same material varied but that average curves drawn with respect to the points gave characteristic results similar for the three metals. These curves differ from those obtained on single crystals in two respects. The curve for tests on single crystals have a much lower yield strength on the 45° section and approach infinite stress values when compressed in the 0° and 90° directions.[4] The yield strengths for the 45° compression in the three cases is approximately 63% of the values for the 0° compression. It should be noted, however, that in many of the 0° compression tests the specimen took as great a stress as 2,000 lbs. per square inch without any strain being noticed. This was not true for the 90° compression tests. The relation between the 0° and the 90° values is not a constant but varies from

[4] Schmidt, W. "Kristallstruktur und praktische Werkstoffgestaltung am Beispiel des Elektronmetalls," Zeitschrift fur Metallkunde, Vol. 25, 1938.

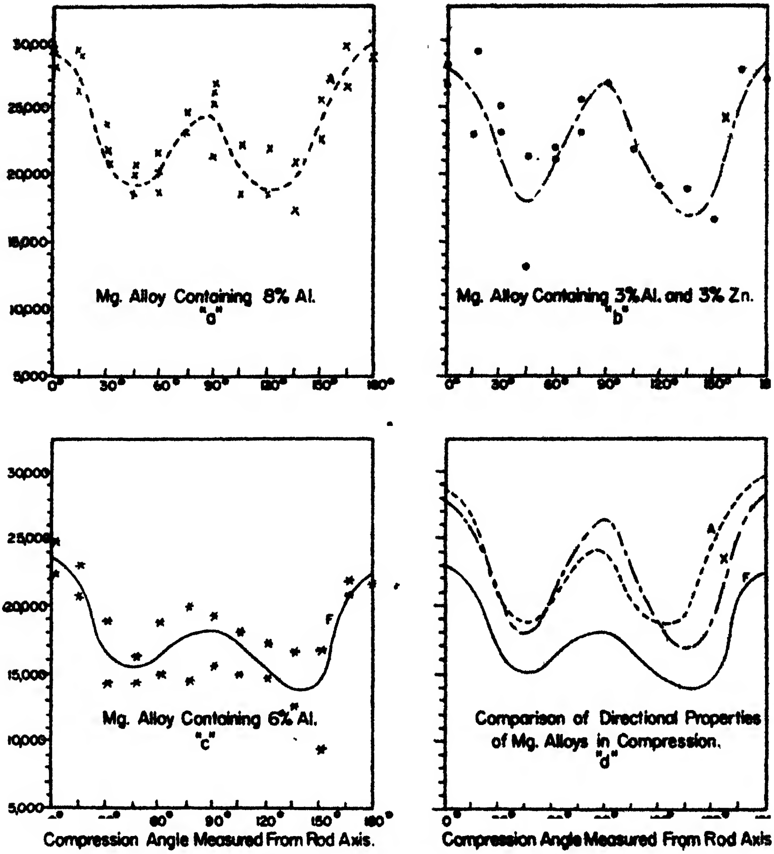


Fig. 6. Directional properties of magnesium alloys in compression.

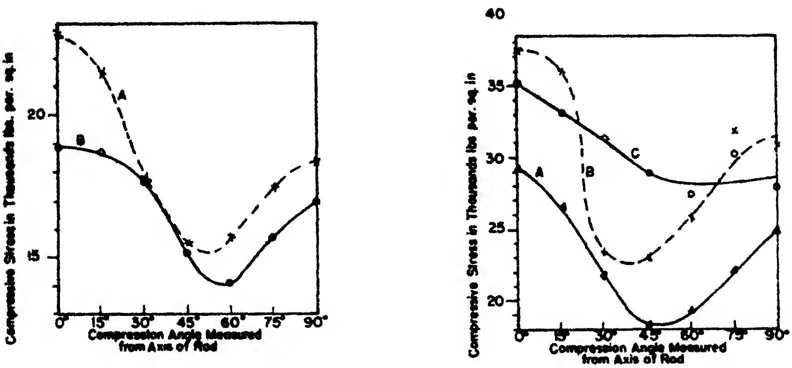
97% to 75%. This ratio is evidently a function of the stringer effect which micro-structures revealed to vary considerably from specimen to specimen.

A comparison of the behavior of the three metals is given in Figure 6d. The 8% aluminum alloy exhibits practically the same changes and strengths as the alloy containing 3% aluminum and 3% zinc. The 6% aluminum is the weakest, particularly its yield strength for the 90° test. This low strength is to be expected as additions of aluminum up to 19% increase the strength of these extruded alloys.[5]

[5] Gann, J. A., "Magnesium Industry's Lightest Structural Metal," S.A.E., 1931.

The author has also found that the 6% alloy would not age while the other samples showed considerable aging effects.

The effects of annealing on the yield strengths and directional properties is given in Figure 7a. This alloy was annealed 18½ hours at 800°F. Recrystallization and some grain growth was evidenced following annealing. It was to be expected that the strength would decrease with the elimination of the working effects but whether the orientations of the new recrystallized grains would be random or follow the



7a 7B

Fig. 7a. Effect of annealing on directional properties. Magnesium alloy containing 6% Aluminum. A. In as received condition. B. Annealed 18¼ hours at 800°F.

Fig. 7b. Effect of aging on directional properties. Magnesium alloy containing 8% aluminum. A. In as received condition. B. Aged at 420°F. for 73 hours, following a 800°F. anneal. C. Aged at 390°F. for 112 hours, from as received condition.

original preferred pattern was open to question. Figure 7a shows that the annealed metal has directional characteristics similar to the original extruded rod. This agrees with the work of Schiebold and Siebel[6] in which they found the recrystallized structure to have no deviation from the originally worked structure when the annealing temperature was up to within approximately 100°F. of the melting temperature.

Figure 7b gives the effects of aging on the directional properties of alloy containing 8% aluminum. It is seen that when the aging follows a preliminary anneal that the directional characteristics of the metal are maintained. In this case the recrystallized grains followed

[6] Schiebold, E. and Siebel, G., "Study of Magnesium and Its Alloys," Zeitschrift dur Physik, Vol. 69, p. 458.

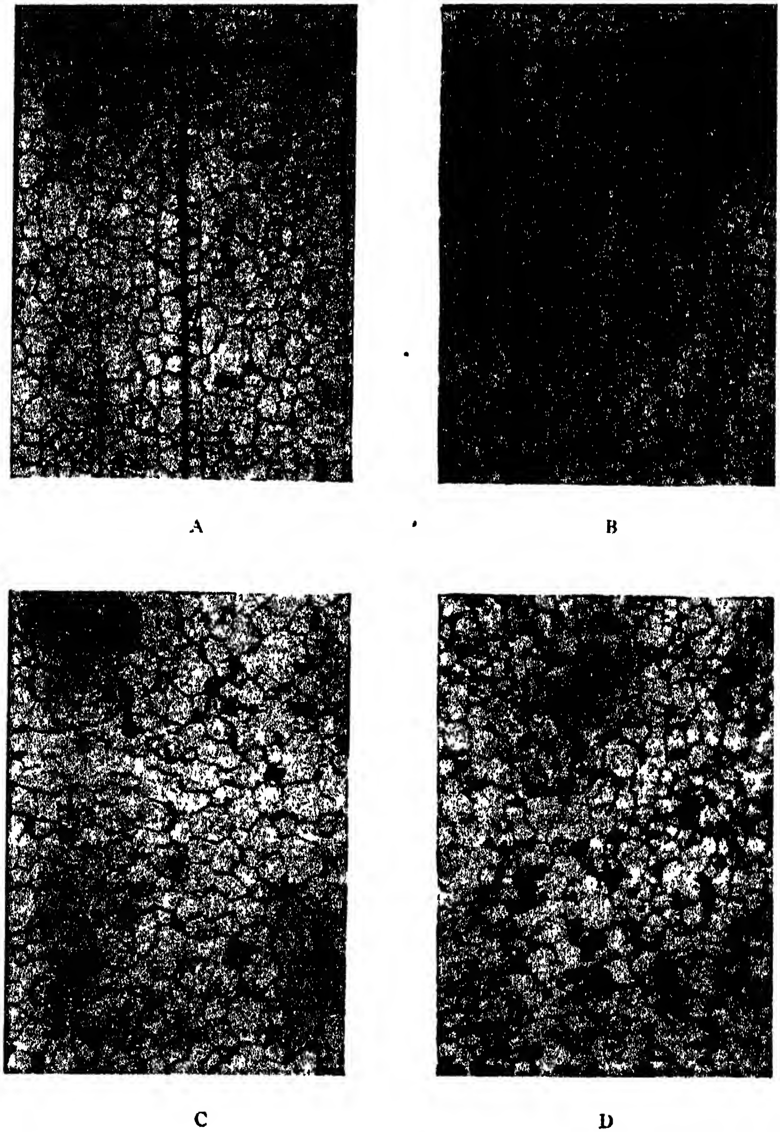
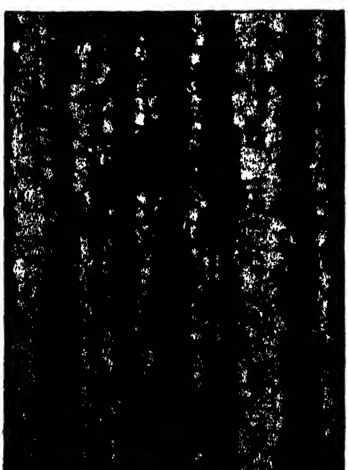


Fig. 8. Changes in micro structures for 390°F. aging from extruded condition. A, B, and C are longitudinal sections aged 0, ½ and 8½ hrs. D is perpendicular section aged 8½ hrs. 100X.

E

F



G

H

Fig. 8. Changes in micro structures for 390°F. aging from extruded condition. E is a perpendicular section aged 3½ hrs. F, G and H are longitudinal sections aged 10½, 16½ and 61 hrs. respectively. 100X.

the same orientation pattern of the original structure and the precipitation although increasing the strength of the metal did not break up the directional pattern. The micro-structures show that the precipitation areas did not arrange in stringer formation but distributed uniformly throughout the metal. This was not true for the specimens that were aged from the "as received" condition. In this case the precipitation followed along the original stringers and this could help account for the curve in Figure 7b representing this condition not having a dip at 45°. The precipitation increased the strength and the fibered structure to an extent that the precipitation stringers and not the individual lattice orientation governed the properties. To illustrate this condition the micro-structures of Figure 8 are presented. These micro-structures show the development of the precipitation stringers with aging. Figure 8E is given as additional evidence of the directional characteristics of the metal. At the beginning of aging the temperature is sufficiently high to cause a partial anneal. This produced a twinning which was visible on perpendicular sections of the rod only as shown in Figure 8.

SHEAR TESTS

Two different types of shear tests were made. In one case the cubes were sheared parallel to the axis of the rod while in the other tests the shearing surfaces were across the axis of the rod. This difference is best understood by referring to Figure 9 which shows the shearing planes for the two cases as applied to a typical cube. The shear block pictured in Figure 3 was used for these tests.

Figures 9a and 9b give curves very similar to those obtained for the yield stress values in compression. These curves are for the case of shearing in a plane parallel to the rod axis and give the maximum shear stress for the various shear angles used. The curves for the alloy containing 8% aluminum was made up from an average obtained from two sets of tests while the curve for the 6% alloy was made up from three sets of tests. The directional properties associated with these curves must be tied up with the direction of the long axis of the hexagonal basal plane and possibly with the precipitation stringers also having a part. These curves are not to be compared with the yield strength values given in Figure 6. If it was possible to do this then

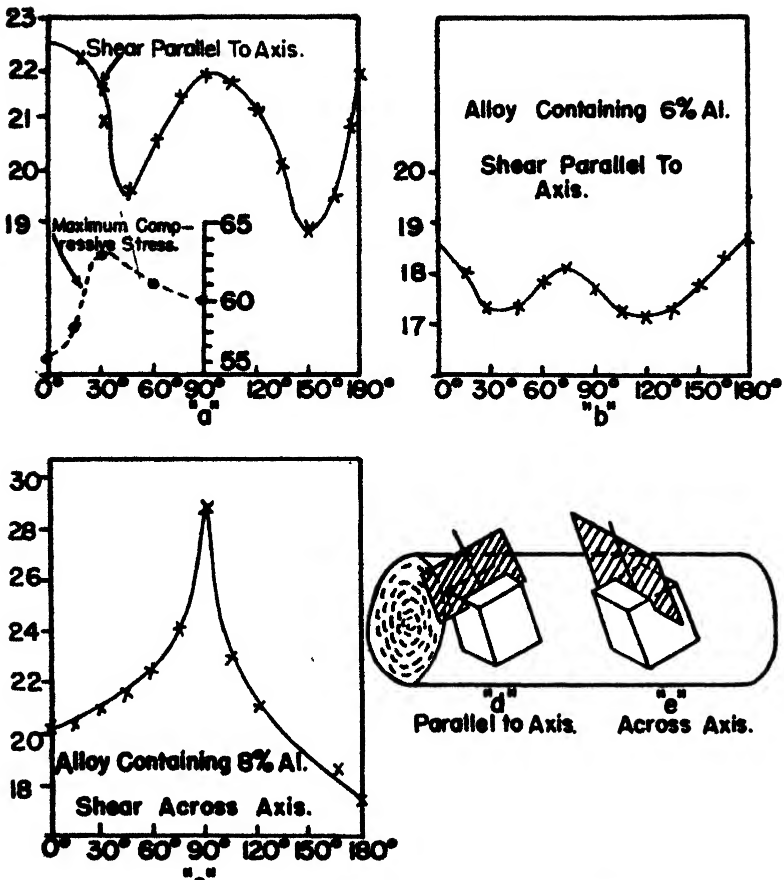


Fig. 9. Shear parallel to and across the axis.

the curves of Figure 9a and 9b would be out of phase by 45°. The maximum shear stress in compression specimens acts on a plane making 45° with the direction of the compression stress and is equal numerically to one-half the compressive stress. This means that when Figure 6 shows a low compressive strength when the cubes were cut at an angle equal to 45° with the axis that in reality it meant a low shear strength on a plane making a 45° angle with the compression stress. This plane of low shear strength then becomes the 0° plane which Figure 9a and 9b give as the strong planes. From this it may

be concluded that Figures 9a and 9b which represent the maximum shear strengths cannot be tied up with the yield strength.

It was possible, however, to make a tie-up between the maximum shear stress curves with the results of the maximum compressive strengths. In compressing the cubes considerable plastic flow took place before failure with the heights of the cubes being permanently compressed as much as 20%. Accompanying this the original first planes of slip at the yield point were changed in direction to conform to conditions of easiest working. When final failure took place the orientation of the original planes lost most of their original significance. When shearing parallel to the rod axis the deformation takes place between basal planes which are planes of weakness. As it was practically impossible to obtain conditions of pure shear these planes rearranged themselves for the conditions of easiest working. This makes it possible in this case to secure a correlation between the curves for maximum shear and maximum compressive stress. Such a relation is expressed in two curves of Figure 9a. The curve of maximum compressive stress was obtained from the average of two sets of tests. The low 0° compressive strength indicates a low shear strength on the 45° plane which is an agreement with the shear stress stress curve. The high compressive strength between the 30° and 45° plane indicates a high shear strength on the planes 45° from these planes which agrees with the high shear values on the 0° and 90° planes of the upper shear strength curve. It will be noticed that the shear stresses at failure are not equal to one-half the compressive strengths on planes 45° removed. This may have been due to the fact that the cubes tested for obtaining the separate curves were cut from different rods.

The curve in Figure 9c was obtained for shear in planes across the axis and differs appreciably from the curve of Figure 9a. It is believed that this curve can be correlated in part with the yield strength curves of Figure 6. In this case the shear is in a direction across the basal planes. This gives a greater strength and less plastic flow. The actual slip planes at failure are believed to be very similar to those at which yielding took place so that some relation exists between Figure 6 and Figure 9c. The fractures for these tests are quite different from those obtained when shearing parallel to the axis.

The smaller deformation and the type of fracture tie in with the above explanation. Figures 10a and 10b show two specimens that were sheared in the shear block shown in Figure 3b. Figure 10a was sheared parallel to the rod axis and Figure 10b was sheared across the axis.

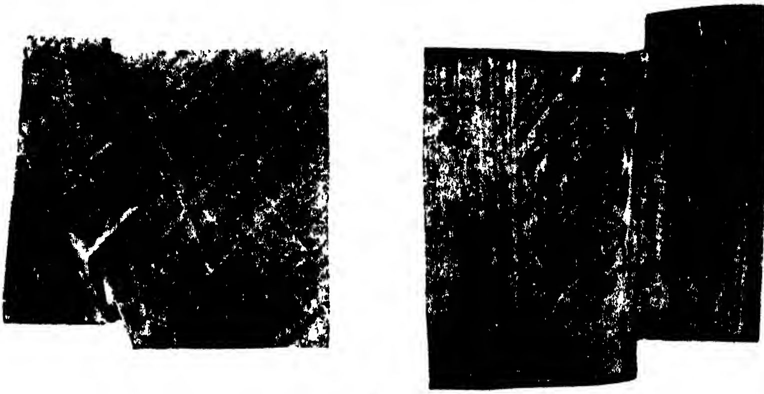
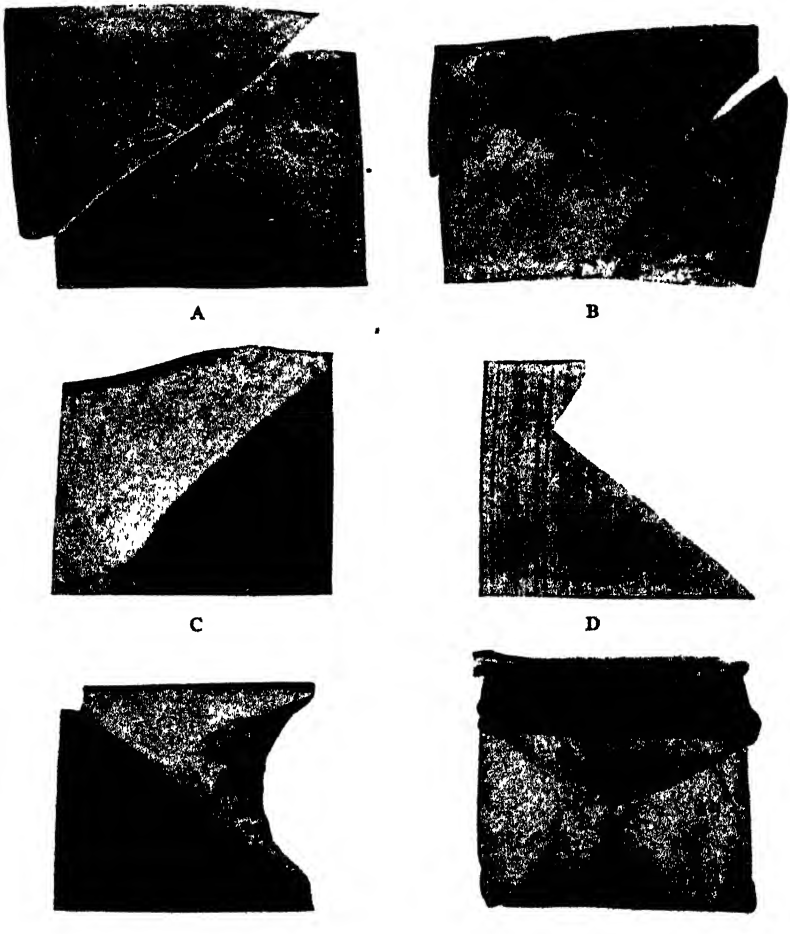


Fig 10. Fractures resulting from shear tests.

The first specimen shows considerable distortion before failure while the second specimen shows that fracture took place on the plane of easy slip.

In comparing curves of Figures 6 and 9c the low compressive strength on the 45° plane is explained by the low shear strength on the 0° plane. In compression there were four sets of planes making 45° with the compression axis. Failure took place on the weakest plane. When compressed 45° with the axis the failure was always a shear failure on the 0° plane and not on the 90° plane. Figure 11 shows some interesting fracture pictures. 11a is the typical single shear fracture while 11b shows fracture to have occurred on the series of weak shear planes. 11c is a specimen having a continuous shear plane made up of two halves meeting on the long diagonal of the cube. 11d failed on three planes two of which are visible and the third not revealed in the picture. 11e also had three fracture planes. 11f showed a specimen failing in the form of two pyramids with all the possible planes of slip coming into play. This specimen was compressed in the direction of the rod axis.

An interesting observation concerning differences in strength for the same angle of shearing was recorded. When shearing on the 0° plane which was parallel to the axis it was found that the strength when shearing in one direction varied appreciably from the strength in the other direction. This difference for the alloy containing 8% aluminum was as much as 22% and was due to the effect of the direction of the original working on the strength in that direction.



A B C D E F

Fig. 11. Fractures resulting from compressive tests.

Some Geologic Aspects of the Magnesite Deposits of Washington

Harold E. Culver, Head, Department of Geology.

So long as the magnesite demand was limited to the manufacture of refractory products, the size of the deposits in Washington was largely an academic problem. It was certain there was an ample supply to meet needs at the current rate of utilization for a long time to come.

With the introduction of new metallurgical processes for the production of metallic magnesium or of compounds suitable for the manufacture of light structural alloys, it becomes desirable to learn what resources exist, both has to purity and as to amounts.

On that account the whole matter of the geologic aspects of the magnesite deposits should be reexamined with a view to determining what factors are important, and of these, which are determined or determinable and which must remain indeterminate in advance of actual operations. In the following paragraphs there is attempted an evaluation of certain facts and some hypothetical considerations. By this means it is hoped to arrive at a restatement of the problem of estimation of our magnesite reserves.

Most of the known deposits of magnesite of Washington are in Stevens County and lie within the Stensgar dolomite, a magnesian formation in the Stevens series of Weaver. Recent studies of this group of Paleozoic sedimentary and associated igneous rocks have provided a better basis for their stratigraphic interpretation than was available earlier.

Investigations by Dr. W. A. G. Bennett of the State Geological Survey show that the sequence of rock formations in the magnesite area includes the Addy quartzite at the top, followed by the Huckleberry greenstone and a conglomerate which may be in unconformable relations to the beds below. There follows a thick argillite which includes not only a quartzitic formation, but the Stensgar dolomite as

well. Another unconformity is suggested at this point in the section, and below this zone lies an argillite formation of great but unknown thickness which includes some additional dolomitic zones which so far have not yielded any magnesite. This latter argillite includes most of Weaver's original Deer Trail formation. Throughout most of the magnesite belt the beds trend slightly east of north, extending from near Chewelah southwesterly for some thirty miles.

Even the Stensgar formation does not extend continuously for this distance, but is interrupted and appears as a series of elongate masses. It is not clear whether this is an original distribution or one due to later diastrophism. In the latter case, two possibilities arise. The dolomite may have been squeezed or stretched into separate segments, or it may have been broken by faults. It is not impossible that both processes may have been involved, although the faulting is more likely so far as present data go. In either case an original continuity is assumed. On the other hand no facts so far advanced preclude the possibility that the original deposition was in lenticular masses. Faulting, known to be present, may have separated the masses further.

Within the dolomite, the magnesite itself is present in ill-defined masses, making up only a small part of the Stensgar formation at any point. As a whole it represents only a small fraction of this stratigraphic unit. Some little study has been made of the matter of the total tonnage of high grade magnesite present in the Stensgar formation. Estimates have been based on varied data and accordingly they vary from a few to many millions of tons. Some early calculations of individual deposits gave figures of as much as one million tons in each of several areas. A later estimate by the United States Bureau of Mines placed the total amount of high grade magnesite at ten million tons for the whole group of deposits.

Development of these beds began in 1916 and was rapid during the years of the World War. Subsequently, with reduction in demand, many of the original quarry openings were closed and further study of reserves was precluded. As a matter of fact, there has not yet been made any comprehensive examination of the States reserves in this resource. The reason is not far to seek. In making such calculations, the investigators had to formulate certain basic assumptions

as to dimensions, purity, and continuity. And back of all of these assumptions was the generally unrecognized factor of origin. On this, more than on any factor, must the estimates be evaluated today, for upon the genesis alone depends the adequacy or inadequacy of each calculation.

The more important, measured by probability, of the origins so far advanced fall into two main groups. First there are those which regard the magnesite as an original deposit, and second, those which regard it as a secondary deposit formed from the dolomite by some process of solution and redeposition. In the first group are two distinct ideas, one suggesting the magnesite was formed as an original marine deposit at the time of the dolomite sedimentation, while the other provides for the later addition of magnesium carbonate through the medium of thermal magnesium-bearing waters of magmatic origin. Without going into the matter in any detail it may suffice here to state that the field evidence includes no facts which suggest that either of these hypotheses is correct. The extremely irregular occurrence of the magnesite in the dolomite belt serves, rather, to emphasize the improbability that the present deposits of magnesite are original. Nor is there evidence of the introduction of thermal waters in the presence of minerals other than magnesite within the supposed impregnated zones of the rocks.

A variant of these "original deposit" theories supposes a sediment of mixed salts of magnesium and calcium to have been laid down in the first place. Then, by some unspecified, but not improbable, process the lime carbonate was removed before there was opportunity for dolomite, the double carbonate, to be formed, thus leaving the magnesium carbonate as found today. This last hypothesis may really be considered a member of both groups since it involves both an original magnesian sedimentation and a subsequent modification, or metamorphic phase, by percolating solutions.

In the second group of hypotheses may be included those involving primarily a change in the composition of the original carbonate rock through the agency of percolating solutions resulting in the deposition of magnesite within the mass of the dolomite. No reference is made to thermal conditions and hence cold, probably meteoric, waters may be assumed to have been the active medium of alteration.

Without relating detailed points of evidence, it is perhaps enough to point out that many, if not most, of the physical and chemical features of the magnesite deposits appear to fit in very well with the idea of alteration of an original dolomitic mass. The distribution of the magnesite, its variability in content of quartz and calcite, the minute interfingering of magnesite and dolomite, and in some instances a gradation, are all features which favor a secondary, or alteration, hypothesis.

In addition to the factors listed above, there is the structure of the rocks to be considered. It is widely recognized by geologists that solutions penetrate rock formations effectively only where the rocks are sufficiently fractured. The whole series of metamorphic sedimentary rocks here under consideration is abundantly fractured. But much of the fracturing has come about after the magnesite was formed. It becomes necessary, then, to determine what part of the fracturing took place prior to the development of the magnesite. This has not yet been done. The bearing of this matter on any thesis of genesis which involves percolating waters is too obvious to need amplification here.

The foregoing summary of hypotheses serves to suggest the inadequacy of present data for working out the problem of origin of the magnesite. And even cursory examination of the question of estimation of tonnages reveals that assumptions of dimensions of deposits below the surface, as well as of their purity, must depend upon the genesis assumed. Thus the depth to which the deposits will extend will be far different on the basis of meteoric water alteration than upon the basis of an original marine origin.

Disregarding this important factor altogether, there still remain unsolved questions of continuity and purity, upon the correct solution of which the whole calculation of tonnages must depend. Those familiar with the field and laboratory data obtained in the course of investigations of these magnesite deposits are always impressed with the marked irregularity of the magnesite masses. Variations in character, physical as well as chemical, lack of uniformity in boundaries, differences in structure, these and other irregularities point to the high improbability of estimating, even roughly, tonnages of magnesite of certain purity still in reserve. This is true of even those parts of

the formation that can be examined at the surface. It requires no further evidence to indicate the improbability of accuracy in estimates involving masses presumed to lie below the observable surface zone.

In the present state of our knowledge it would seem that the past production records, where available, would provide a working basis for estimation. But here, too, unexpected difficulties arise to plague the investigator. It is found that even this mode provides an all too slender basis for calculation.

That much magnesite of requisite purity lies near the surface is generally believed. Nor is the basis for this belief lacking. But when it comes to actual calculation of available tonnages, the assumptions that must be made are so important, so far-reaching, that we can but conclude our data are as yet inadequate.

An estimate of one million tons of high grade magnesite as a minimum seems over-conservative to most students of the question of reserves. Yet an estimate of twenty times as much may be equally far off at the other end. On one point there is no question, that the true figures cannot be determined on present information.

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Torsional Stress Concentration Factors and Rigidity Characteristics of Grooved Shafting

by James G. McGivern

Lately Assistant Professor of Mechanical Engineering

The Place of Research in Higher Education

By H. V. Carpenter

Dean, College Mechanic Arts and Engineering

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Torsional Stress Concentration Factors and Rigidity Characteristics of Grooved Shafting

James G. McGivern
Lately, Assistant Professor of Mechanical Engineering

I. INTRODUCTION

By means of various experimental procedures, numerous investigations have been made to determine stress-concentration factors at fillets, holes, and keyways in shafting subjected to torsional stresses. The many studies have been justified because of the importance of this problem to the machine designer, the inadequacy of the theory of elasticity for computing these factors, and the need for explaining the lack of agreement of the results obtained by the various methods. The results and interpretations of these studies have added some to our information on stress-concentration factors, but have contributed little, if anything, to an evaluation of the effect of fillets on shaft rigidity. The effect of the length of shafting between fillets, and, in particular, the extreme case which considers circular grooves, has had very little work done upon it.

The object of this report is to present the results of experiments made to determine stress-concentration factors and the shaft-rigidity characteristics of circular shafting having grooves and subjected to torsional stresses. The effects of the ratios of outside diameter of shaft, of the groove radius, and of the length between fillets, to the small diameter of the shaft are included. The data are presented by means of tables and curves, and correlations are made with other studies.

II THE PLASTIC FLOW METHOD

The Plastic Flow Method is based on the fact that mild steel follows Hooke's Law of proportionality up to its yield stress and then appreciable deformation takes place without additional stress being applied. This may be interpreted as meaning that, when large

deformations or appreciable deviations from Hooke's Law are observed in mild steel, the stress associated with these strains is equal to the yield stress. The application of this principle is termed the "Plastic Flow Method."

Fig. 1 presents two torsional stress-strain diagrams, the second differing from the first by having two fillets included in the gage length. The typical diagram of Fig. 1a gives the yield stress of mild steel in shear as 28,000 lbs./sq. in. Fig. 1b shows that yielding at the fillets on section "m" takes place when the computed stress

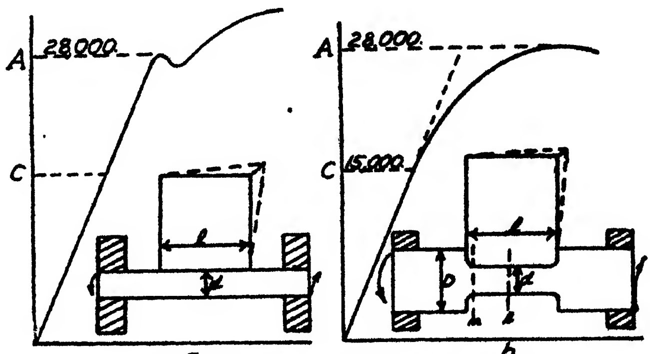

Fig. 1. Principle of Plastic Flow Method.

on the outside of section "l" is 15,000 lbs/sq. in. This gives a stress-concentration factor equal to 1.86, which is equal to the true stress of 28,000 lbs/sq. in. at the fillets divided by the calculated stress of 15,000 lbs/sq. in. as predicted by the simple torsional equation. A more complete description of this method is to be found in a report which is confined to the effects of fillets alone and of which this report is a continuation.[1]

III. TESTING PROCEDURE

Specimens were prepared from 2" and 2½" diameter hot-rolled SAE 1020 steel both in the as-received and in the annealed condition. For the initial tests the rod was cut and the pieces prepared so that every other specimen had a uniform diameter equal to the small

[1] J. G. McGivern, "Torsional Stress Concentration Factors at Fillets", State College of Washington, Engineering Experiment Station Bulletin No. 58, February, 1939.

diameter of the grooved specimen. This made it possible to obtain the true yield stress of the material for determining the stress-concentration factor of the grooved specimen. Experience showed that, although the yield stress of the material varied, it was not necessary to take every other specimen as a calibration specimen, and that within the accuracy of the experiment every fourth or fifth specimen was sufficient.

The circular grooves were cut in the specimens by means of special cutting tools. These tools were prepared by brazing ball bearings on to the end of steel stock and grinding the bearings down to the desired diameter. The depths of the grooves were varied in order that the effect of the ratio of the large diameter to the small diameter of the shaft could be investigated. Groups of specimens were prepared having the ratios of their large diameter to small diameters equal to 1.5, 1.33, 1.2, and 1.1. Within each group the diameter of the groove was varied. The lengths of the specimens were such that for all cases the distance from the jaws of the torsion machine to the groove was greater than one and one-half times the large-shaft diameter.

Fig. 2. Setup for Torsional Concentration Tests.

The set-up for taking data is shown in Fig. 2. The arms attached to the specimen are twenty-inches long, and the dial micrometer attached to the end of one of the arms reads in thousandths of inches. The twisting moment was applied at a rate of one-sixth of a turn per hour and was regulated by hand until sufficient data were obtained, after which the speed was increased and the specimen twisted to failure.

Stress-strain diagrams were plotted, and from these curves the stresses corresponding to plastic yielding were obtained. The true slopes of these curves were also recorded, and from these values the equivalent length of the shaft was computed.

IV. STRESS CONCENTRATION FACTORS

Fig. 3 represents some of the stress-strain curves obtained from specimens having a ratio of large diameter to small diameter equal to 1.5. These curves show how the stress corresponding to plastic

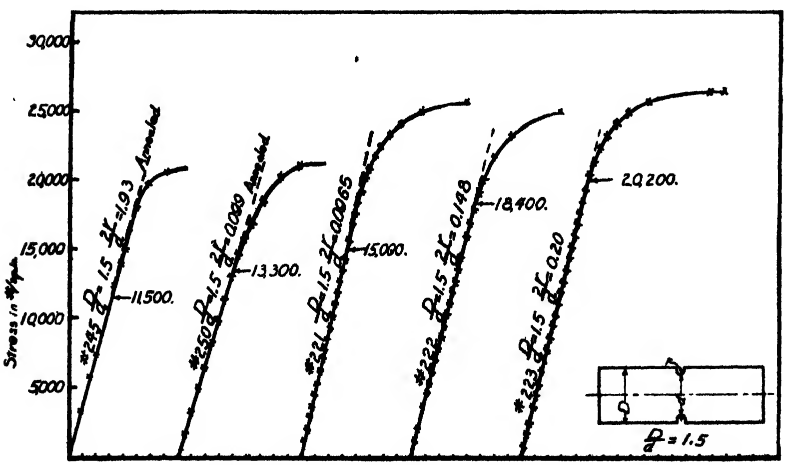

Fig. 3. Typical Stress Strain Diagrams.

yielding varies with the radius of the circular groove. The value of the true yield stress was determined from the calibration specimens. Specimens number 245 and 250, having the low yield stress values were annealed prior to testing. Although the yield stresses varied considerably among the many specimens, the ratio of yield stress

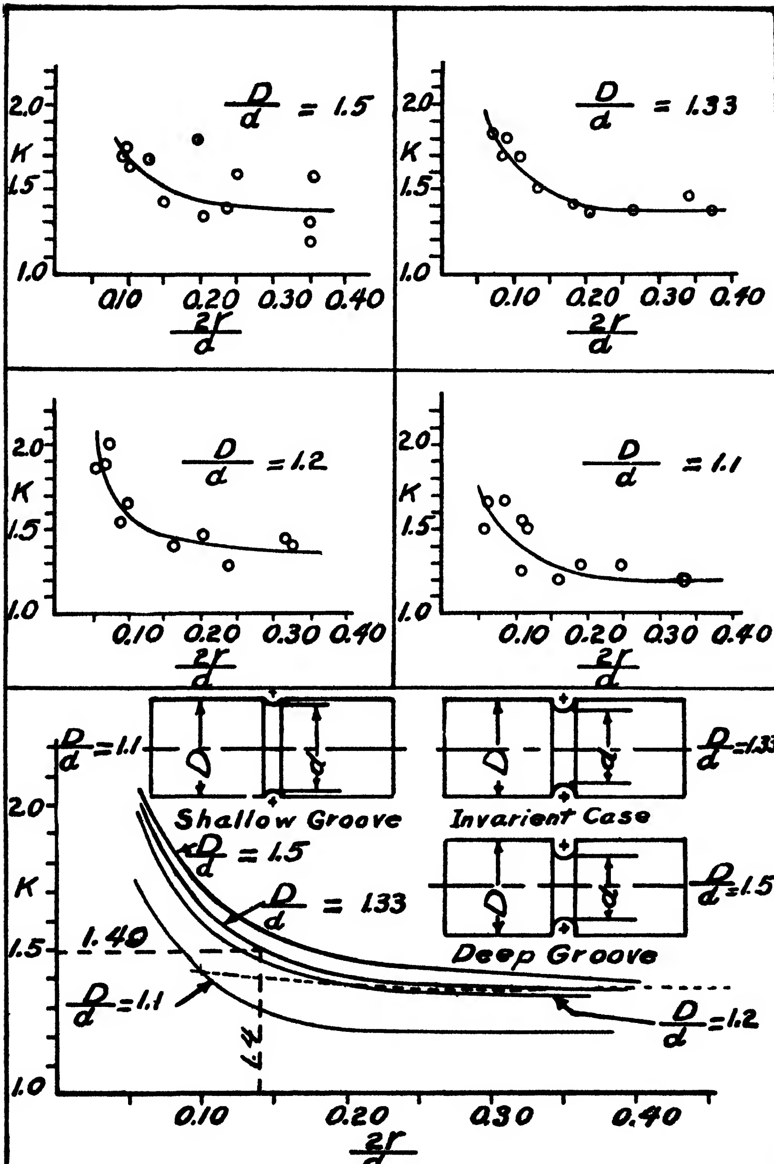

Fig. 4. Torsional Stress Concentration Factors at Grooves.

to plastic flow stress is apparently independent of the yield stress and a function of the geometrical properties of the specimen alone. This is illustrated by the distribution of the individual stress concentration factors with respect to the average curves for the various diameter ratios as given in Fig. 4. These same curves are drawn to a larger scale at the bottom of Fig. 4, which shows the relation between the concentration factors, the diameter ratios, and the groove-to-diameter ratio.

Because semi-circular grooves were used, it follows that three situations are possible. The center of the groove may be located on the surface of the shaft or it may be either outside or inside the shaft. In the first alternative, the depth of the groove is just equal to the groove radius and this has been termed the invariant case.[3] If the groove center is outside the shaft, the groove depth is less than the groove radius and the groove is called a shallow groove. When the center is inside the shaft, the groove depth become greater than the groove radius, and we have so-called deep groove. For the invariant case

Values of 2r/d corresponding to this case for various values of D/d are plotted in Fig. 4 and represented by the dotted line. This line indicates that all shafts having semi-circular grooves whose depths are equal to their groove radii have a practically constant stress-concentration factor whose value is equal to 1.4. If the stress-concentration factor is considered made up of the effects of the ratio of diameters and of the groove radius, this states that, when the effect of one increases, the effect of the other decreases by the same amount, the sum being kept a constant. For small ratios of shaft diameters, the stress concentration is due mainly to the effect of the groove of small radius, whereas for large values of D/d the value of the concentration is dependent upon D/d much more than upon the groove radius. The dotted line of Fig. 4 separates the values obtained from deep grooves, which are above the line, from the shallow grooves, which are represented below the line.

The application of these curves to a specific case may be assumed as follows: A shaft 1.67" in diameter has a circular groove of .175"

[3] M. M. Frocht. "Photoelastic Studies in Stress Concentration", *Mechanical Engineering,* August, 1936

diameter cut into it so that the reduced diameter is 1.25″. In this case the ratio of D/d equals 1.33 and of 2r/d equals .14. The lines of Fig. 4 indicate that the stress at the groove is 1.49 times the stress that would be computed if the simple torsional equation is used and the calculation is made on the basis of the small diameter of the shaft.

V. EFFECT OF GROOVES ON SHAFT RIGIDITY

For calculating the natural frequency of shafting, it is necessary to know its torsional rigidity. For shafts of uniform diameter, this is expressed in terms of the modulus of elasticity of the material, the length of the shaft, and the polar moment of inertia of the cross-section. When the shaft changes its diameter with accompanying fillets and groves, the determination of the rigidity becomes more complex. By measurement of the slopes of the stress-strain diagrams, it is possible to determine from these tests the apparent modulus of elasticity for the various ratios of diameters and fillets. These values are listed along with other significant data in Table I.

The true modulus of elasticity being a function of the material alone, it is common practice to assume a constant modulus for a given shaft and alter the dimensions to give the rigidity characteristics as found by experiment. This may be done by either decreasing the diameter or increasing the length to make up for the effects of the fillets and grooves. The usual procedure is to change the length, and this is done by application of the simple Coulomb equation as discussed in the preceding bulletin of this series.[1]

Table I gives values for the apparent modulus of elasticity and the ratio of this value to the true modulus. It also gives the length increment and the ratio of this increment to the distance between shoulders of the large shaft. This length increment "Δl" is the amount that must be added to the distance between the shoulders in order that the correct rigidity of the shaft can be calculated by the use of the true modulus of elasticity of the material in the simple equation. For deep grooves and for the invariant case, the length to which the increment must be added is equal to the diameter of the groove.

Table I. Concentration and Rigidity Characteristics of Grooved Shaftings

No.	Dia.	2r/d	Plastic Flow Stress	Yield Stress	Stress Con. k	Slope of Modulus Line G_1	l = 2r	GA/G_1	$\Delta l/l$	Δl
					D/d = 1.1					
100	1.393	.065	18,000	29,500	1.64	1,450,000	.091	8.55	7.55	.666
251	1.500	.058	15,500	20,700	1.53	1.650,000	.087	7.50	6.50	.652
242	1.500	.162	19,500	23,400	1.20	4,240,000	.242	2.93	1.93	.466
243	1.500	.106	18,600	23,200	1.25	4,080,000	.165	3.04	2.04	.332
227	1.500	.245	21,000	27,000	1.28	8,850,000	.368	1.40	.40	.146
226	1.500	.119	20,000	30,000	1.50	6,450,000	.178	1.92	.92	.164
229	1.500	.0794	17,500	28,700	1.64	4,360,000	.119	2.84	1.84	.219
228	1.500	.186	19,500	28,500	1.46	8,550,000	.279	1.45	.45	.126
232	1.500	.0587	20,700	30,700	1.48	2,700,000	.088	4.6	3.6	.317
225	1.500	.33	24,000	28,500	1.19	13,000,000	.495	.955	.045	.0225
					D/d = 1.2					
231	1.545	.160	17,500	24,500	1.4	6,230,000	.247	1.99	.99	.244
230	1.550	.088	18,000	27,500	1.525	3,930,000	.119	3.16	2.16	.257
120	1.545	.237	20,600	26,300	1.278	5,200,000	.366	2.39	1.39	.51
117	1.545	.322	19,000	26,800	1.41	8,000,000	.498	1.55	.55	.272
118	1.545	.077	12,500	25,000	2.00	1,840,000	.119	6.74	5.74	.682
93	1.545	.076	25,600	48,000	1.875	1,820,000	.118	6.82	5.82	.686
92	1.543	.098	28,800	48,000	1.665	1,960,000	.151	6.32	5.32	.805
91	1.543	.196	35,000	48,000	1.45	4,500,000	.310	2.75	1.75	.542
94	1.543	.055	26,000	48,000	1.846	1,370,000	.086	9.06	8.06	.692
90	1.543	.318	32,000	48,000	1.450	6,060,000	.492	2.05	1.05	.516
					D/d = 1.33					
244	1.593	.174	18,000	23,000	1.44	12,210,000	.241	1.012	.012	.00289
252	1.593	.110	12,500	21,000	1.68	4,450,000	.164	2.79	1.79	.276
116	1.599	.262	19,500	26,500	1.36	6,220,000	.566	1.995	.995	.364
114	1.593	.307	17,000	24,500	1.44	6,400,000	.430	1.94	.94	.405
115	1.599	.081	15,000	25,500	1.70	1,800,000	.115	6.89	5.89	.665
113	1.599	.524	19,500	25,200	1.29	10,100,000	.732	1.228	.228	.167
85	1.54	.0857	15,500	26,600	1.77	2,160,000	.115	5.75	4.75	.546
86	1.593	.205	19,800	26,600	1.34	6,490,000	.286	2.26	1.26	.36
87	1.583	.129	16,800	28,200	1.60	3,600,000	.179	3.45	2.45	.458
98	1.550	.068	15,800	25,000	1.81	1,760,000	.091	7.05	6.05	.55
95	1.393	.353	22,000	29,000	1.32	8,800,000	.492	1.41	.41	.202
					D/d = 1.5					
111	1.193	.233	18,000	24,300	1.35	5,500,000	.278	2.26	1.26	.35
110	1.233	.348	16,000	25,000	1.55	4,920,000	.480	2.52	1.52	.654
112	1.228	.096	15,600	26,000	1.7	2,020,000	.119	6.14	5.14	.611
221	1.255	.0965	15,000	26,000	1.75	2,330,000	.119	5.32	4.32	.515
222	1.233	.146	16,400	26,000	1.41	3,950,000	.183	3.14	2.14	.392
223	1.233	.200	20,200	26,600	1.32	5,230,000	.247	2.56	1.56	.335
245	1.255	.193	11,500	20,600	1.79	6,140,000	.258	2.02	1.02	.245
250	1.255	.099	13,300	21,400	1.61	3,250,000	.122	3.82	2.82	.344
96	1.218	.247	16,100	25,500	1.58	5,700,000	.301	2.18	1.18	.356
99	1.235	.36	22,400	26,500	1.18	7,500,000	.432	1.656	.656	.283
97	1.235	.121	29,000	48,000	1.65	3,550,000	.151	3.5	2.5	.378

The ratio of the length increment to the length varies with the ratio of shaft diameters and with the ratio of the groove diameter to the small-shaft diameter. For each ratio of large to small diameter a smooth curve is obtained when the ratios of lengths are plotted against the ratio of groove diameter to small shaft diameter. Fig. 5 gives the distribution of the individual points with respect to the average curves obtained for each ratio of diameter. The enlarged set of curves is made up of a combination of the individual ones and shows to an enlarged scale the combined effect of the ratio of the shaft diameters and the ratio of groove diameter to small-shaft

diameter. These curves show that the ratio of groove diameter to shaft diameter has a much greater influence on the length increment ratio than does the ratio of shaft diameters. This length increment is not a function of the diameter of the groove alone, as can be seen by an inspection of Table I. The curves bring out the effect of a very small groove to an exaggerated degree. This is because the groove diameter is equal to the assumed length of the small shaft, and this, which is divided into the "△l", decreases as "l" increases, wherefore the quotient increases rapidly. For very large groove diameters the curves show the change in length to be very small and the slope of

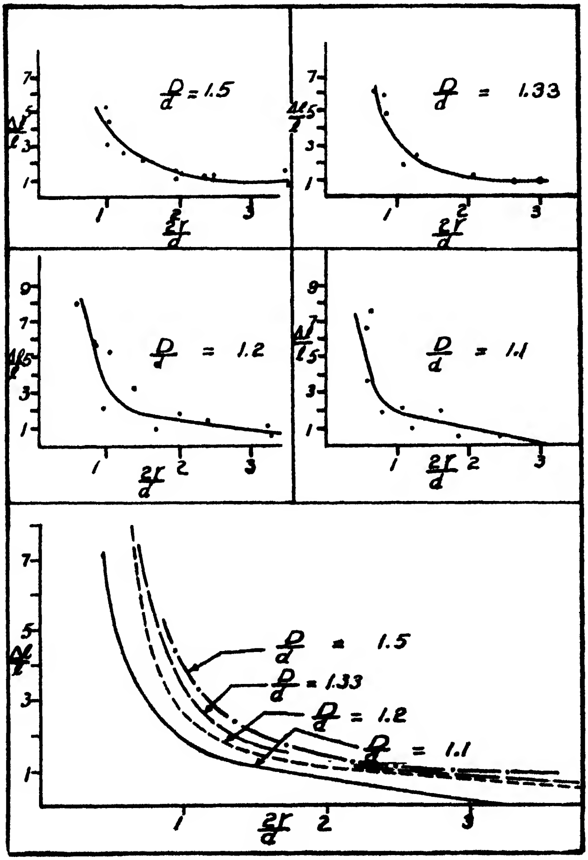

Fig. 5. Length Increment as Affected gy Shaft Diameters and Groove Radius.

the curves indicate that the length increment ratio may become nega-tive for sufficiently large values of 2r/d. This is very reasonable as very large groove diameters would increase the assumed length of the small shaft and the effect of the stress concentration at the beginning of the fillet would be more than offset by the increased rigidity given by the increasing diameter of the shaft between the beginning of the fillet and the shoulders of the large shaft.

VI. EFFECT OF LENGTH OF SHAFT ON RIGIDITY AND STRESS CONCENTRATION

The curves previously presented considered the effects of grooves alone. For a given radius and ratio of diameters the grooved speci-men gives the maximum stress concentration and change in shaft rigidity. By an increase in the distance between the shoulders of the large shaft the original groove is replaced by two fillets and this dis-tance between shoulders is called the length of the small shaft.

Table II. Effect of Length on Torsion Characteristics

No.	Dia.	2r/d	Stress Con. k	l/d	2r	G_1	GA/G_1	$\Delta l/l$	Δl	l
56	1.395	.205	1.54	.205	.286	5,720,000	2.17	1.17	.335	.286
258	1.395	.196	1.30	.358	.275	9,600,000	1.29	.29	.145	.500
299	1.395	.196	1.26	.716	.275	11,750,000	1.055	.055	.055	1.00
67	1.331	.206	1.29	1.5	.275	12,100,000	1.025	.025	.05	2.00
257	1.395	.196	1.24	2.87	.275	12,520,000	1.006	.005	.02	4.00
300	1.395	.199	1.25	5.74	.277	12,550,000	1.0025	.0025	.0185	8.00
85	1.34	.0857	1.77	.0825	.115	2,160,000	5.74	4.74	.545	.115
301	1.395	.087	1.66	.358	.121	5,700,000	2.18	1.18	.59	.5
302	1.395	.087	1.400	.716	.121	8,080,000	1.54	.54	.54	1.0
12	1.397	.079	1.60	1.43	.111	10,550,000	1.17	.17	.34	2.0
303	1.395	.087	1.35	5.74	.121	11,920,000	1.045	.045	.36	8.0

The effect of this length was determined for two different values of 2r/d on specimens having D/d equal to 1.33. The results of these tests are given in Table II and represented graphically in Fig. 6. The two sets are for the two groups of specimens given in the table having average values of 2r/d equal to .20 and .085 respectively. These results are in agreement with the principles of Saint-Venant and show that the effects of length are practically zero when the length, for the case of two fillets, becomes greater than twice the diameter. For lengths shorter than this, the effects are very pronounced, particularly on the rigidity characteristics. The increase of approximately twenty-two per cent in the stress concentration at the grooves as compared to that of a fillet of the same radius in a large shaft is not nearly so large as

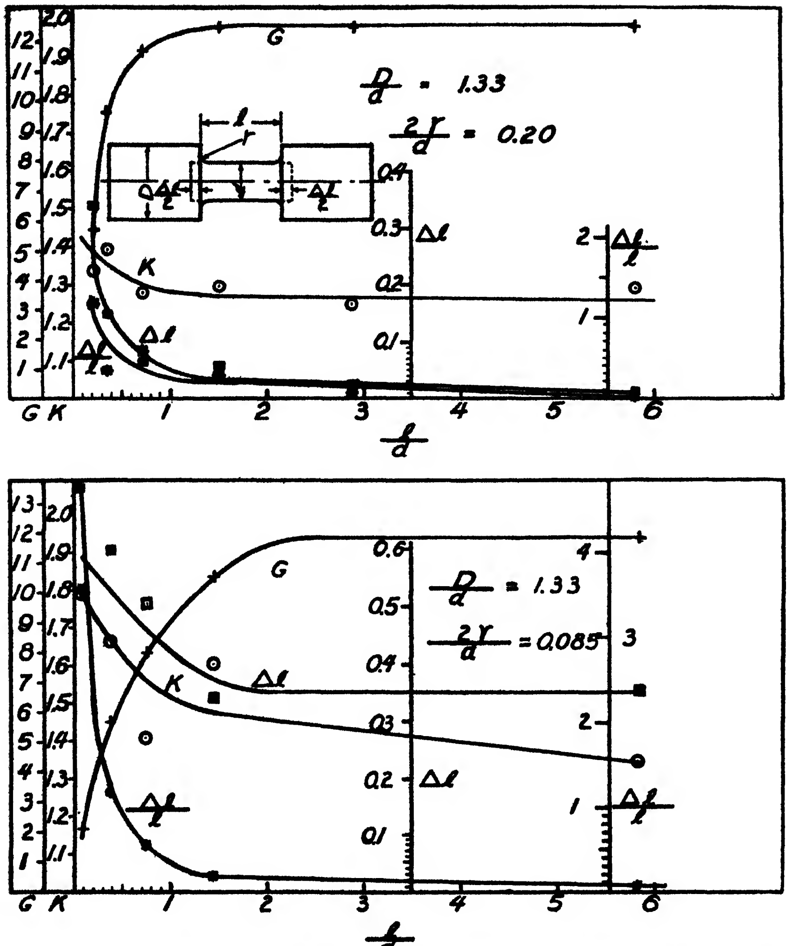

Fig. 6. Effect of Length on Stress Concentrations and Shaft Rigidity Characteristics.

the percentage changes in G, Δl, and Δl/l, as given in Fig. 6. The scale gives G in 10^6 lbs. per square inch.

The breaking strength as determined from the maximum twisting moment was practically the same for all the specimens regardless of length. Macro-structures revealing the strain patterns of specimens that had failed and those in the process of failing showed that plastic flow started at the place of tangency of the fillet and the small shaft.

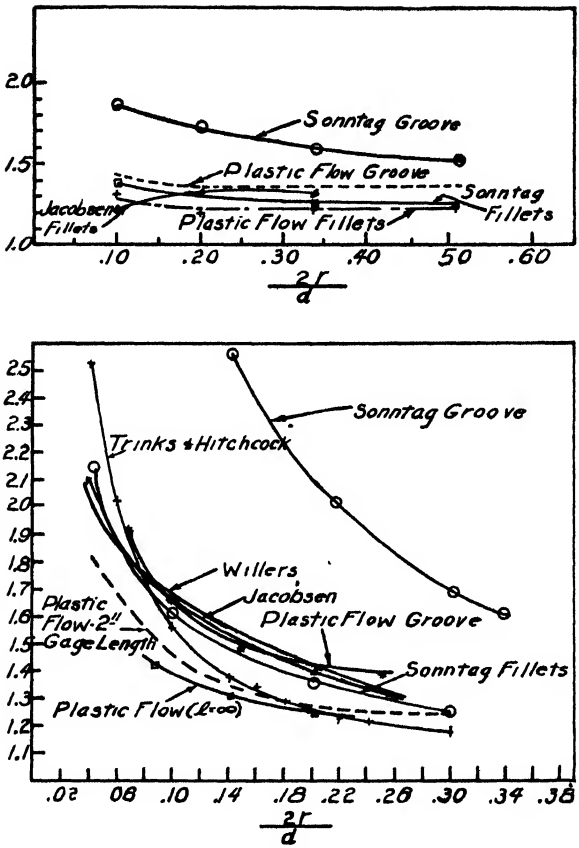

Fig. 7. Comparison of Data Obtained by Various Methods.

Correlation of Results with Other Studies

The principal methods used to determine torsional stress-concentration factors have been the graphical method of Willers,[3] the electrical analogy of Jacobsen[4], the approximate method of Sonntag[5], the

[3] Willers, F. A., "Die Torsion eines Rotationskörper um sine Achse," *Zeit für Math. und Physik,* Vol. 55, 1907.

[4] Jacobsen, L. S., "Torsional Stress Concentration in Shafts", A.S.M.E., *Trans.,* 1925, Vol. 47.

[5] Sonntag, R., "Zur Torsion von vunden Wellen mit veränderlichen Durchmesser", *Zeit. für angewandte Mathematik und Mechanik,* 1929, Vol. 9.

brittle material method[6], the fatigue methods[7-8], and the plastic flow method.

The applications of most of these methods have been limited to shafts with fillets. Sonntag, however, gives two equations, one for grooves and one for fillets. By substituting the relation expressed in equation (1), he reduces the general equation for the grooves to a simplified expression applicable to the invariant case. The same can easily be done for the general fillet equation, and the results compared to those obtained by the plastic flow method are given in Fig. 7a. These results show that the fillet concentration factors agree reasonably well and are fairly constant in both cases. For the case of the grooves the agreement is not good, nor is the ratio of the groove values to the corresponding fillet values the same for the two methods. In this figure is also represented a curve for fillets taken from Jacobsen's data which correlates well with the other methods.

Fig. 7b gives a comparison of values obtained by the various methods for both fillets and grooves of the deep and shallow type These curves all apply to the one ratio of D/d equal to 1.33 and show there is considerable difference in the results reported by the separate methods. The results of Willers, Jacobsen, and Sontag agree reasonably well for the case of the grooves These curves correlate with the plastic flow results for the case of grooves, but vary appreciably from the plastic flow fillet curves The curve obtained by plotting Sontag's equations for grooves is very high and does not seem reasonable. Included in the figure is also a curve obtained by plotting an equation of Trinks and Hitchock.[9] The results obtained from the brittle-material method and fatigue method are considerably below any of the curves represented.

ACKNOWLEDGEMENTS

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[6] Seeley, F. B., & Dolan, T. J., "Stress Concentration at Fillets, Holes and Keyways", Bulletin 276, Engineering Experiment Station, University of Illinois, June, 1935.
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[8] Dolan, T. J., "The Combined Effect of Corrosion and Stress Concentration," Bulletin 293, Engineering Experiment Station, University of Illinois, April, 1937.
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The Place Of Research In Higher Education

H. V. Carpenter

The long and seemingly discouraging progress of us human beings toward better things has in modern times brought about many hopeful signs, such as a better appreciation of the things which count toward a richer culture, a sounder system of relations with our fellow men, and much advance in caring for ourselves in material ways. Men have multiplied their superiority over some of the higher animals largely through mastering methods of passing knowledge on to succeeding generations so that once a contribution is made to civilization it becomes the useful tool or guide to all who come after. In this way we have advanced in many ways in spite of our pitifully weak abilities to discover and develop new and valuable arts, ideas, and practices.

So much time and effort is required in the schools to maintain our present culture and mastery of our arts and skills, that it is easy to forget that maintenance is one thing but progress is quite another. In routine educational work students are led in well-known and tested paths to be able to do what their elders are doing. To push out into the unknown in the hope of solving some mystery of science or developing some better artistic or literary style, or devising some new technical aid to good living; any of these requires a working mastery of the known related art, much exercise of the imaginative faculties, and a will to experiment with the unknown. Men like Galileo, Sir Francis Bacon, and Leibnitz deserve very great credit not only in their own special fields, but in general, for they did much to teach the art of research. The Greeks were mighty men but did not learn that actual experimentation to try out new ideas was a vital means of advancement.

Modern scientific and technical researchers have long since accepted as a guiding principle that, for the best results, work in the laboratory must proceed side by side with theoretical analysis. Analysis suggests possible tests, and tests yield results which lead to a sounder basis for thought or may open unexpected possibilities for advance in

a new way. Work of this type demands and develops the type of resourcefulness that makes progress possible, and educators are well agreed that the experience gained in carrying through a good piece of investigation has values in developing the mind along hopeful lines that cannot be attained in any other way.

Since any attempt to answer hitherto unanswered questions may be classified as research, the field includes every phase of human interest and activity. Because complete knowledge of any subject seems unattainable, it is not surprising that research is in progress in every conceivable direction. Science and technology have shown greater progress, partly because the technique for scientific research has been better developed, but principally because results in regard to material things are much more definite than in the field of human relations. This enables the scientist to accept and use the results of others and go on to the next question. Research may be divided into two overlapping types: one that includes the study of questions which are interesting but which do not show promise of immediate usefulness, the other the more "practical" type wherein problems pressing for solution are undertaken. Much of the latter type falls into the field of engineering research and frequently involves consideration of the financial matters always involved in any useful development. On this account there has been in recent years a remarkable increase in research largely of the industrial type, carried on by large manufacturing concerns. Most of their work relates to their own commercial product and results in improved processes or a better product for their firm, although some concerns are doing valuable research on broader problems. In the leading colleges and universities today, research is an accepted part of their service to society as well as a valuable teaching method. Advanced students are past their most serious need for classroom instruction, and experience has shown that their development is brought about very effectively by giving them a moderate amount of guidance while they undertake a research problem. From the nature of the case one cannot be sure of a useful result from every research venture. It is a gamble with the unknown in which a negative answer or no answer at all may be the result of a hopeful study. Even this result has value frequently in pointing toward some other means of attack or in showing what was wrong with the reasoning that led

to the study. Nearly every division of the State College of Washington has some research under way. The well-financed work in matters related to agriculture in the land-grant colleges has justified itself in ample fashion both here and in the other schools.

Other lines have had only minor support, yet have done much both to advance scholarship and to make major contributions in the way of new and useful information, new ways of doing things, and new products from natural resources. Much of this work is being done in the State Metallurgical Laboratory, which is now collaborating with the branch of the U. Ss. Bureau of Mines newly established here, and in the Engineering Experiment Station. Both of these divisions have as a part of their purpose the training of advanced students in research. The mining group have found a splendid opportunity for usefulness in developing methods for concentrating, separating, and purifying the state deposits of copper, manganese, and magnesium. Notable results have been achieved, and a number of advanced students have been trained in research methods.

In the Engineering Experiment Station over a twenty-year period, many projects have been examined and those most promising have been undertaken for solution. Over sixty bulletins have been printed describing the work and the results. Some of the more important contributions have included: Relative wear of auto tires on various types of road surface—a report which had world-wide influence and aided in the move toward paved highways; studies in the storage of apples were helpful to the apple industry; fatigue of welded steel was a valuable contribution to the knowledge of permissible loads for welded joints; relative lubricating value of different types of auto engine oil was studied by a new method with positive results and a major influence on this most important item in auto maintenance; a thorough study of electric heating of homes has established relations that will be of much use in the near future. Others include a study of methods of measuring the flow of water; characteristics of alloys of magnesium; domestic stokers; refrigeration and freezing units for the farm; etc.

These have been of a very practical type. In the basic natural sciences and in mathematics the work is usually more fundamental; that is, it deals with the establishment of new or more accurate knowl-

ledge of certain physical phenomena or with the development of new mathematical processes, all with no definite attempt to find an immediate application but rather to contribute to our scientific foundations and methods of analysis. In all of these activities faculty members and advanced students are both the initiators and the workers. The interest in, and ability to carry on research varies greatly among people of similar all-round ability. Some men are primarily teachers; others like to think of every unsolved question as a challenge. Both groups are useful, but it is in the research type that hope for progress lies.

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